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ELECTROMAGNETIC ACCELERATION OF A VARIABLE-MASS PLASMA

by Donald J. Vargo

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SUMMARY

Nonlinear one-dimensional rail-accelerator equations were solved with an analog computer by treating mass as a variable. The rail mass-erosion coefficient was chosen from previously published vacuum-spark experiments. A set of nondimensional equations was constructed containing three parameters, the electromechanical interaction, the circuit damping, and the initial mass. Solutions are presented over ranges of these parameters.

Energy efficiencies of 40 percent for the first cycle and greater than 55 percent for the final values were obtained for the best combination of these parameters. If switching were used to store the remaining system energy, theoretical first-cycle efficiencies of over 60 percent would be realized.

The results indicate that the well-designed accelerator should have the lowest possible parasitic resistance and inductance and mass erosion rate, while capacitance, initial voltage, and inductance per unit length of rail should be large.

INTRODUCTION

Pulsed-plasma accelerators are being considered as thrustors for electric propulsion systems. Other feasible applications include their use as fusion-injection devices, material-coating guns, and plasmoid generators. Hence, many theoretical analyses have been conducted in order to achieve both an understanding of and better performance from these devices. Millsaps and Pohlhausen (ref. 1) applied both analog and digital techniques to solve the set of nonlinear equations describing plasma motion. Artsimovich, et al. (ref. 2) computed the acceleration of small plasma masses under the assumption of zero resistance. Bostick (ref. 3), by assuming constant current, was able to uncouple the nonlinear equations and obtain solutions. Shock (ref. 4) ignored the rail resistance per unit length and derived asymptotic solutions to the equations. Mostov, Neuringer, and Rigney (ref. 5) obtained certain approximate and asymptotic solutions including the effect of rail resistance. All these previous papers have treated the plasma as a slug (a nondeformable body) having constant mass.

In the physical case the plasma mass is, however, not constant. The plasma may pick up mass by sweeping, sputtering, and eroding. Mass may also be lost from the plasma when the magnetic pinch forces are low (near zero current). The importance of this variable mass, therefore, still needed theoretical evaluation.

Kash (ref. 6), recognizing this deficiency of the previous analysis, was able to obtain a closed-form solution to a specific variable-mass case. He assumed that the rail inductance per unit length and the circuit resistance were constant, and he assumed a rate of mass increase such that plasma velocity remained constant.

With the use of an anolog computer, the present analysis solves a more general case by treating the plasma as a slug of variable mass, which is permitted to increase at rates previously determined (by vacuum-spark experiments) (ref. 7). These experiments showed that, in a hard-vacuum plasma discharge, a definite relation exists between the total charge that flows and the total mass eroded for a given material. In the real accelerator system, the presence of the propellant gas might reduce the rate of electrode erosion below that obtained from reference 7; however, this reduced erosion is not considered in this analysis. Also neglected in this analysis are rail resistance, plasma impedance, sheath drops in the vicinity of electrodes, and mass and radiation losses.

Equations of motion are derived on the basis of these assumptions. By normalizing techniques, the equations are reduced to a set containing three nondimensional parameters. Analog solutions that show the effects of the variation of these nondimensional parameters in the equations of motion are presented.

SYMBOLS

A circuit damping parameter, $\sqrt{C_o R_o^2/L_o}$

B electromechanical interaction parameter, $L_1^2 V_o C_o/2kL_o$

C_o capacitance, f

I current, amp

I^* nondimensional current, $I\Big/\sqrt{\frac{C_o V_o^2}{L_o}}$

k mass erosion rate constant, kg/coulomb

k_o value of k corresponding to $B = 1.667$, $m_I^* = 10$

L_o circuit inductance, h

L_1 rail inductance per unit length, h/m

m mass, kg

m^* nondimensional mass, m/kC_oV_o

m_I initial mass, kg

m_I^* nondimensional initial mass

R_o circuit resistance, ohms

t time, sec

t^* nondimensional time, $t/\sqrt{L_oC_o}$

V instantaneous voltage across capacitor, v

V^* nondimensional voltage, V/V_o

V_o initial voltage across capacitor, v

x distance, m

$\dot{x}$ velocity, m/sec

x^* nondimensional distance, xL_1/L_o

$\dot{x}^*$ nondimensional velocity, $\dot{x}/\sqrt{L_o/L_1^2C_o}$

$\ddot{x}$ acceleration, m/sec^2

η efficiency, $\dfrac{\frac{1}{2}\,m\dot{x}^2}{\frac{1}{2}\,C_oV_o^2}$

ψ nondimensional system parameter, $B/2m_I^*A^2$

Superscripts:

$(\dot{\ })$ first derivative with respect to time

$(\ddot{\ })$ second derivative with respect to time

ELECTROMECHANICAL EQUATIONS

In the derivation of the electromechanical equations of motion, the effects of rail resistance are assumed small and are neglected.

Kirchoff's law for the circuit of figure 1 is

$$-V + \frac{d}{dt}(L_o + L_1 x)I + IR_o = 0 \tag{1}$$

The indicated differentiation produces

$$\dot{I} = \frac{V - (L_1 I\dot{x} + IR_o)}{L_o + L_1 x} \tag{2}$$

The energy equation for the circuit at any instant is

$$\frac{1}{2} C_o V^2 + \frac{1}{2}(L_o + L_1 x)I^2 + \int_0^t I^2 R_o \, dt + \int_0^x \frac{d(m\dot{x})}{dt} dx = \frac{1}{2} C_o V_o{}^2 \tag{3}$$

The fourth term on the left side of equation (3) represents the work done in accelerating the mass. After integration by parts, this term becomes

$$\int_0^x \frac{d(m\dot{x})}{dt} dx \equiv \int \dot{x} \, d(m\dot{x}) = \frac{m\dot{x}^2}{2} + \int_0^t \frac{\dot{m}\dot{x}^2}{2} dt \tag{4}$$

where the first term is the kinetic energy at time t, and the second term is the energy lost in accelerating the eroded mass.[1] This eroded mass is accelerated by inelastic collisions with the moving plasma and shows up as random energy, or heat, in the plasma.

Substitution of equation (4) into equation (3) and differentiation with respect to time yield

$$C_o V \dot{V} + (L_o + L_1 x)I \dot{I} + \frac{I^2}{2} L_1 \dot{x} + m\dot{x}\ddot{x} + \frac{\dot{x}^2}{2}\dot{m} = -I^2 R_o - \frac{\dot{x}^2}{2}\dot{m} \tag{5}$$

Substitution of the capacitor equation

$$\dot{V} = -\frac{I}{C_o} \tag{6}$$

and equation (2) into equation (5) yields

$$\ddot{x} = \frac{L_1 I^2}{2m} - \frac{\dot{x}}{m}\dot{m} \tag{7}$$

[1]The presence of this energy loss and its derivation were pointed out to the author by Mr. John Heighway of the Lewis Research Center.

From reference 7 it is found that

$$\dot{m} = k|I| = kC_o|\dot{V}| \tag{8}$$

Therefore,

$$m = kC_o \int_0^t |\dot{V}| \, dt + m_I$$

where m_I is initial mass. For these values of $\dot{m}$ and m, equation (7) becomes

$$\ddot{x} = \left(\frac{L_1 I^2}{2} - kC_o\dot{x}|V|\right) \frac{1}{kC_o \int_0^t |\dot{V}| \, dt + m_I} \tag{9}$$

To nondimensionalize the equations, the following variables are defined:

$$\left.\begin{aligned}
t^* &= \frac{t}{\sqrt{L_oC_o}} \\
V^* &= \frac{V}{V_o} \\
I^* &= \frac{I}{\sqrt{\frac{C_oV_o^2}{L_o}}} \\
x^* &= \frac{xL_1}{L_o} \\
\dot{x}^* &= \frac{\dot{x}}{\sqrt{\frac{L_o}{L_1^2C_o}}} \\
m^* &= \frac{m}{kC_oV_o}
\end{aligned}\right\} \tag{10}$$

In terms of these dimensionless variables, with $\dot{V}^* = -I^*$, the governing equations (2) and (7) become

$$-\ddot{V}^* = \frac{V^* + \dot{V}^*(\dot{x}^* + A)}{1 + x^*} \tag{11}$$

$$\ddot{x}^* = \frac{BI^{*2} - \dot{x}^*|V^*|}{m^*} \tag{12}$$

where

$$m^* = \int_0^{t^*} |\dot{V}^*| \; dt^* + m_I^* \tag{13}$$

The efficiency of the accelerator can be expressed as the ratio of the kinetic energy in the plasma to the initial energy in the capacitors:

$$\eta = \frac{m\dot{x}^2}{C_o V_o^2} = \frac{m^* \dot{x}^{*2}}{2B} \tag{14}$$

The dot now indicates differentiation with respect to t^*, and

$$A = \sqrt{\frac{C_o R_o^2}{L_o}}$$

$$B = \frac{L_1^2 V_o C_o}{2kL_o}$$

The parameter $2B$ is the ratio of the capacitor energy $\frac{1}{2} V_o C_o$ to a reference plasma kinetic energy consisting of the reference mass kC_oV_o and the reference velocity $\sqrt{L_o/L_1^2 C_o}$. Also, as seen from equation (12), B can be considered as the ratio of the mechanical reaction $\frac{d}{dt}(m^*\dot{x}^*)$ to the applied magnetic pressure, which is proportional to I^{*2}. Thus, B will be referred to as the electromechanical interaction parameter. The parameter A can be written as the ratio of the first-order time constant to the second-order time constant $R_oC_o/(L_oC_o)^{1/2}$, and because of its specific dependence on resistance and on the circuit time constants, it will be referred to as the circuit damping parameter.

For the special case of zero erosion, equation (11) is unchanged, but equation (12) becomes

$$\ddot{x}^* = \frac{B}{m_I^*} I^{*2}$$

where B/m_I^* is independent of k. Consequently, the results for $k = 0$ cannot be deduced directly from the solutions of the previous equations but require a special calculation. Fortunately, reference 4 contains a closed-form solution to the equations of motion with zero erosion $(k = 0)$ as time approaches infinity and voltage and current approach zero. From this solution, the maximum efficiency was found to be

$$\eta_{max} = 1 - \frac{2}{(\psi + 1)^{1/2} + 1} \tag{15}$$

where ψ is related to the nondimensional parameters of the present report by

$$\psi = \frac{B}{2m_I^* A^2} \tag{16}$$

RESULTS AND DISCUSSION

To obtain the plasma accelerator performance data, equations (11) to (14) were solved on an analog computer. The general analog program used in obtaining solutions is presented in figure 2.

Solutions for three values of each of the parameters A, B, and m_I^* are presented in figure 3. The data presented are values of nondimensional voltage, current, mass, distance, plasma velocity, and efficiency as functions of normalized time. The ranges of the parameters chosen include values representive of real devices and values a factor of 10 higher and lower.

A phenomenon not noted in previous solutions is that generally the plasma velocity reaches a maximum and then decreases with time. This happens because the drag caused by mass addition (second term of eq. (12)) in time becomes larger than the driving term (first term of eq. (12)) and thus causes the acceleration to become negative. This result must be considered in the design of any accelerator system.

To clarify the effects of the various circuit parameters, maximum plasma velocity is plotted against the circuit damping parameter A for three values of both the initial mass m_I^* and the electromechanical interaction parameter B in figure 4. In general, changes in the value of B affected the maximum velocities much more than did changes in the parameter A. Changing B two orders of magnitude varied the maximum plasma velocity almost two orders of magnitude. A similar change in A varied the maximum velocity approximately a factor of 4. Increasing A reduced the maximum velocity slightly at the largest value of B used. This effect became greater as the value of B was reduced. Increasing the value of m_I^* substantially decreased the maximum velocities reached for all cases of A and B presented.

In figure 5, the maximum efficiency is plotted against the circuit damping parameter A for three values of both the nondimensional initial mass m_I^* and the electromechanical interaction parameter B. The maximum efficiency based on total stored energy obtained for the range of the circuit parameters chosen was 55 percent. Higher values of B are probably unrealistic if erosion mass addition is encountered. In most of the cases shown in figure 3, the efficiency reached a maximum and then decreased. This occurred because the energy losses due to electrode erosion became larger than the incremental gains in the kinetic energy. In the cases where the efficiency did not maximize in the solution time, the highest values recorded were used for the maximum values. In the few cases where this occurred, the slope of the data indicated that the maximum efficiency was not significantly different from the value used. The efficiency, like the maximum velocity, is much more susceptible to changes in the electromechanical interaction parameter B than it is to changes in the damping parameter A. For the maximum values of A and B used, the efficiency was a maximum at values of m_I^* between 0.1 and 10, as shown in figure 5. For lower values of A and B, however, no optimum m_I^* was found in the range investigated.

The effect of the erosion rate constant k is not explicitly evident in figure 5 because it appears in both m_I^* and B. Since both of these parameters change by the same factor with changes in k, however, the effect on efficiency of variations in k can be deduced from figure 5. Typical results in terms of the parameter ψ of equation (16) are presented in figure 6. Here k_0 is the value of k corresponding to $B = 1.667$, $m_I^* = 10$. Also included in this figure is the zero-erosion case as calculated from equation (15). In general, reductions in the erosion rate produced significant increases in the system efficiency. If erosion rates less than those chosen here are achievable, significantly higher maximum efficiencies can be expected.

Plasma accelerators are often designed with a length such that the plasma leaves the gun sometime between one-half cycle (current first returns to zero) and one cycle (current returns to zero for the second time) of discharge. The results shown in figure 3 indicate first-cycle efficiencies of up to 40 percent for the range of parameters chosen. If the capacitor could be disconnected at zero current and the remaining energy could be made available for subsequent discharge, then efficiencies in excess of 60 percent would be possible.

Various circuit parameters such as electromechanical interaction B, circuit damping A, and nondimensional initial mass m_I^* can be investigated to determine which real circuit elements should be varied for good performance. This examination indicates that the values of circuit resistance R_0, circuit inductance L_0, and mass addition constant k, should be made as low as material limitations permit, while the values of capacitance, voltage, and rail inductance per unit length should be made large.

Increasing rail inductance per unit length L_1 tends to concentrate the circuit magnetic energy in the rail area where it is most useful. For this reason it is important to have the ratio of the rail inductance per unit length L_1 to the circuit inductance L_0 made as large as physically practical.

The results of the analysis presented in this report are believed to be reasonably representative of a real plasma accelerator. The choice of a high erosion rate is counterbalanced to some extent by neglecting some rail and all plasma losses. The results indicate that, in spite of erosion, a properly designed plasma engine could attain high enough theoretical efficiencies to remain competitive with other types of high-impulse thrustors.

SUMMARY OF RESULTS

The equations for the rail accelerator were derived by considering plasma mass as a variable. The rate of mass addition from the electrodes as previously obtained experimentally was assumed to be proportional to the absolute value of current flow. Equations were derived that contain three nondimensional parameters, electromechanical interaction, circuit damping, and nondimensional initial mass. Solutions were obtained for a realistic range of these parameters and results were as follows:

1. The mass addition due to electrode erosion reduced the plasma acceleration and in some cases made it negative after a short time.

2. Increases in electromechanical interaction parameter caused large increases in both plasma maximum velocity and accelerator efficiency.

3. Increasing the circuit damping parameter decreased both the maximum plasma velocity and the accelerator efficiency.

4. Increasing the nondimensional initial mass decreased maximum plasma velocity and increased accelerator efficiency except at the largest value of circuit damping considered.

5. Maximum efficiencies as high as 55 percent were obtained, values up to 40 percent being obtained at the end of one cycle for the range of parameters selected. If switching were used to retain the remaining energy in the capacitor bank, theoretical efficiencies greater than 60 percent would be possible.

6. The computed efficiencies, based on the rates of erosion of this report were much lower than those obtained for the zero erosion rate. Consequently, if erosion rates less than those chosen herein can be achieved, higher values of maximum efficiencies can be expected.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, April 7, 1964

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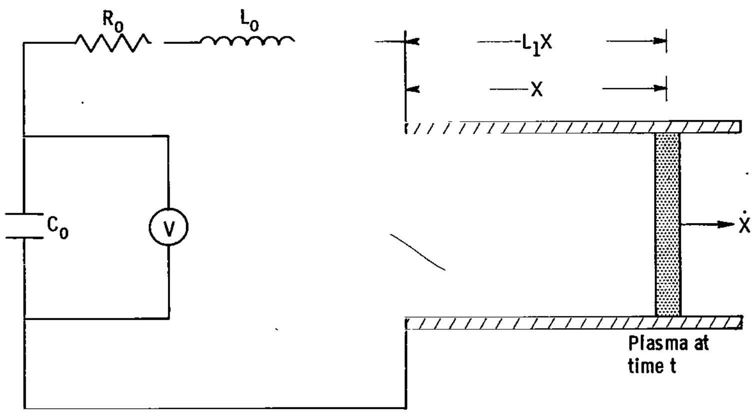


Figure 1. - Equivalent circuit of rail-type plasma accelerator.

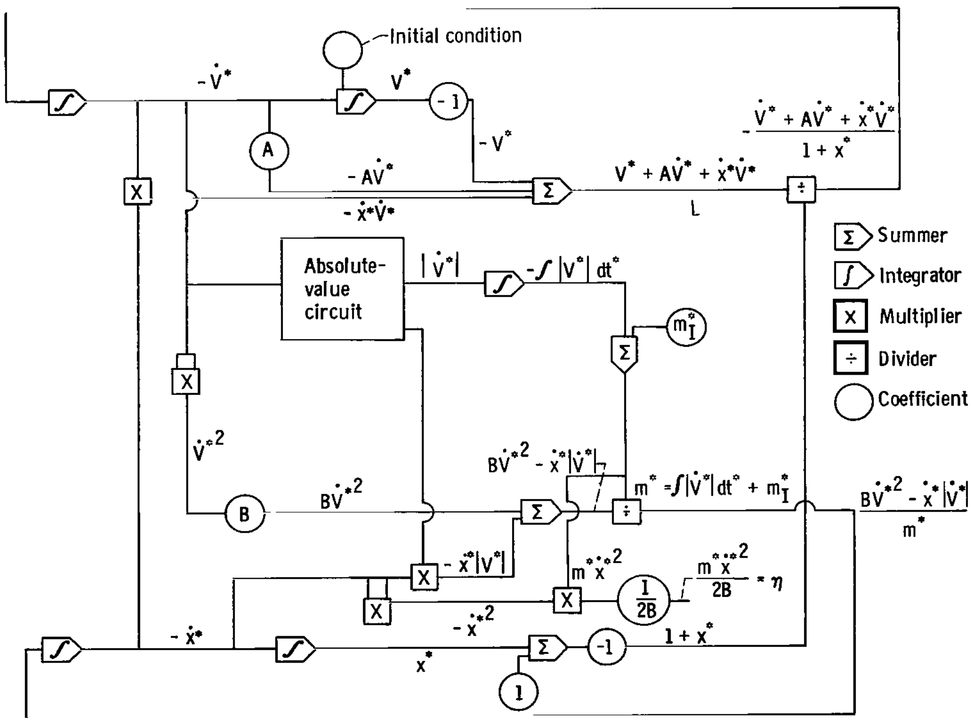
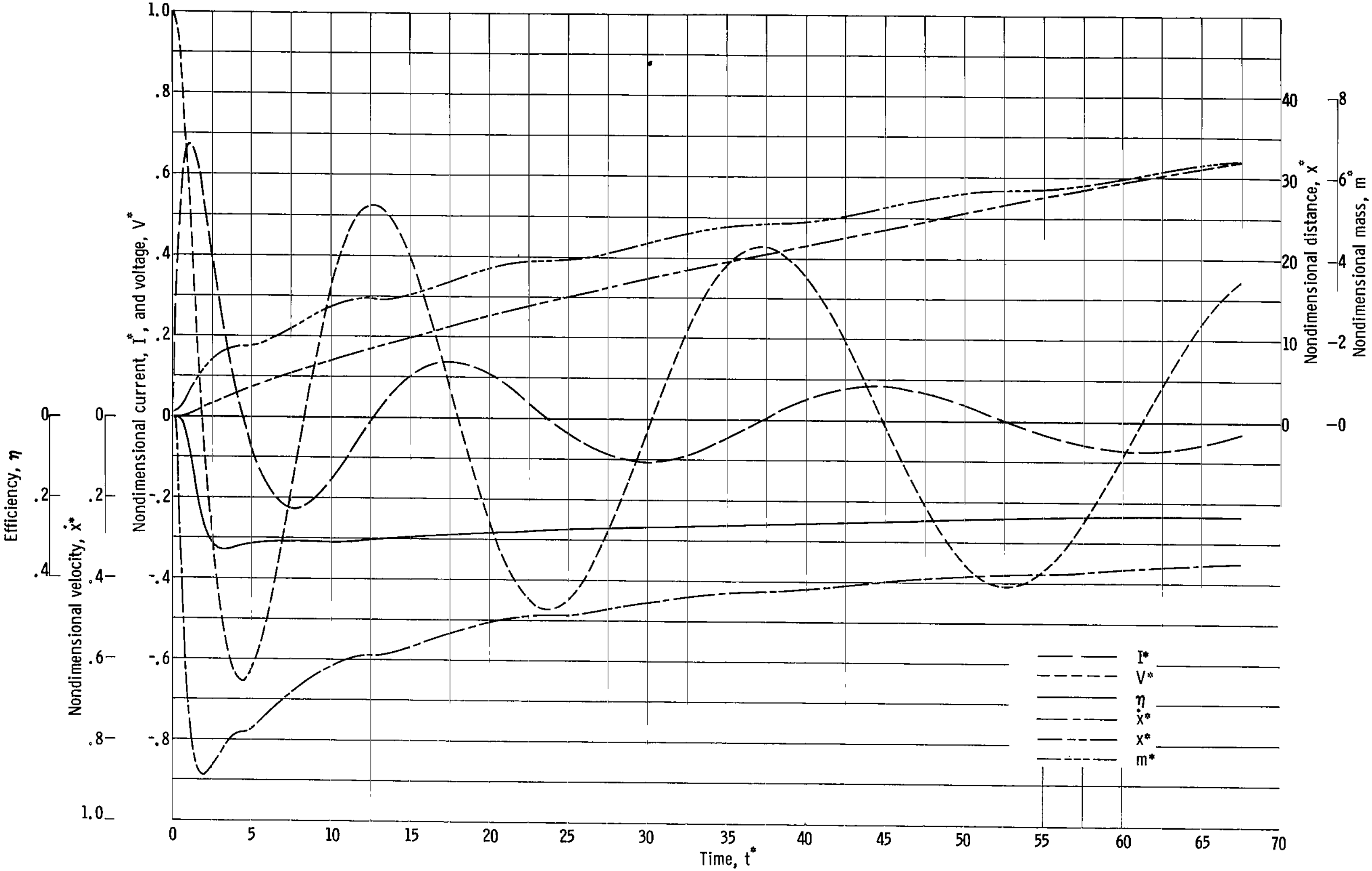


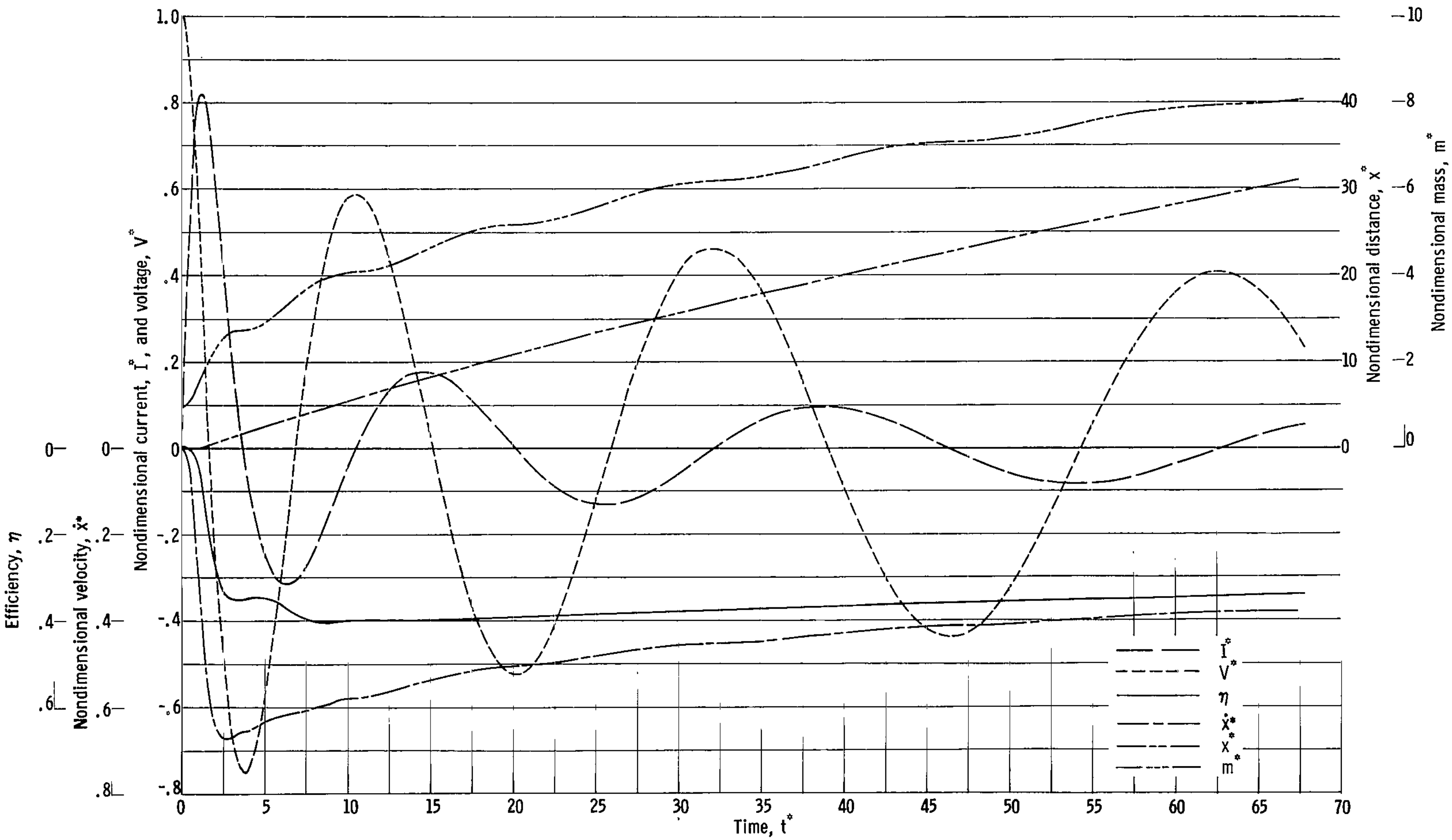
Figure 2. - General analog program for solutions of equations of motion (eqs. (11) to (14)).



(a-1) Nondimensional initial mass, 0.1.

(a) Circuit damping parameter, 0.0022; electromechanical interaction parameter 1.667.

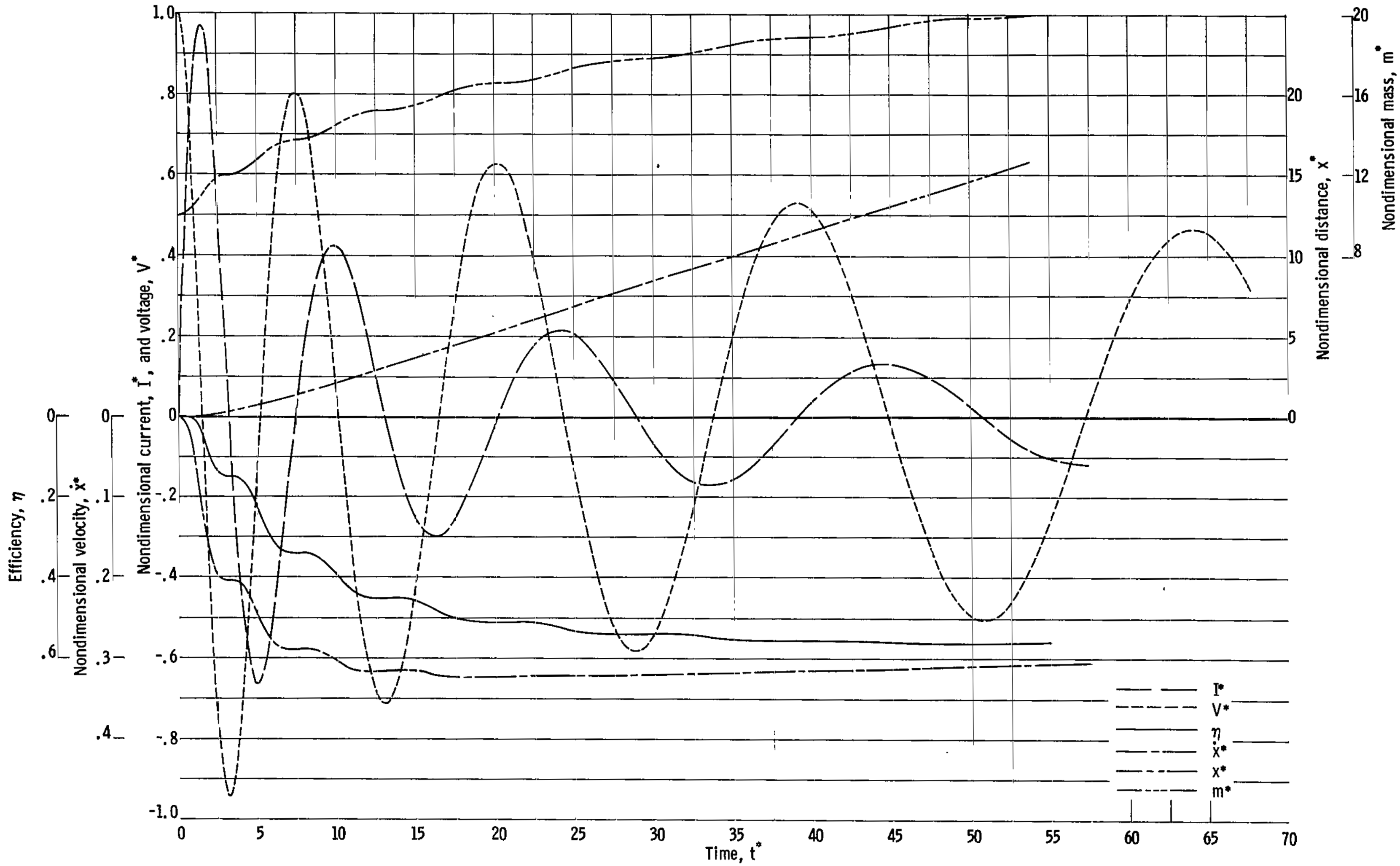
Figure 3. - Analog solutions of plasma accelerator equations.



(a-2) Nondimensional initial mass, 1.

(a) Continued. Circuit damping parameter, 0.0022; electromechanical interaction parameter, 1.667.

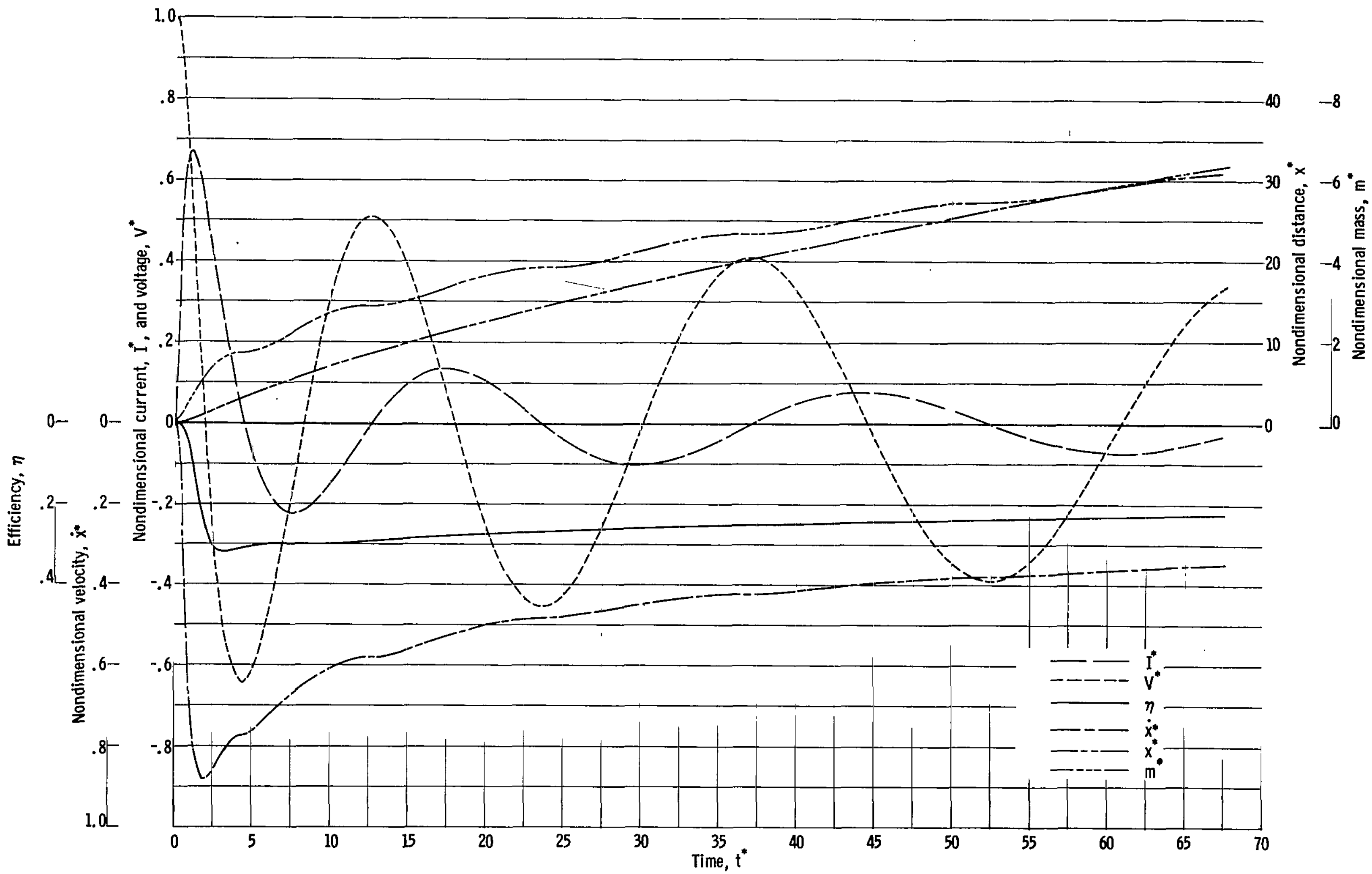
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(a-3) Nondimensional initial mass, 10.

(a) Concluded. Circuit damping parameter, 0.0022; electromechanical interaction parameter, 1.667.

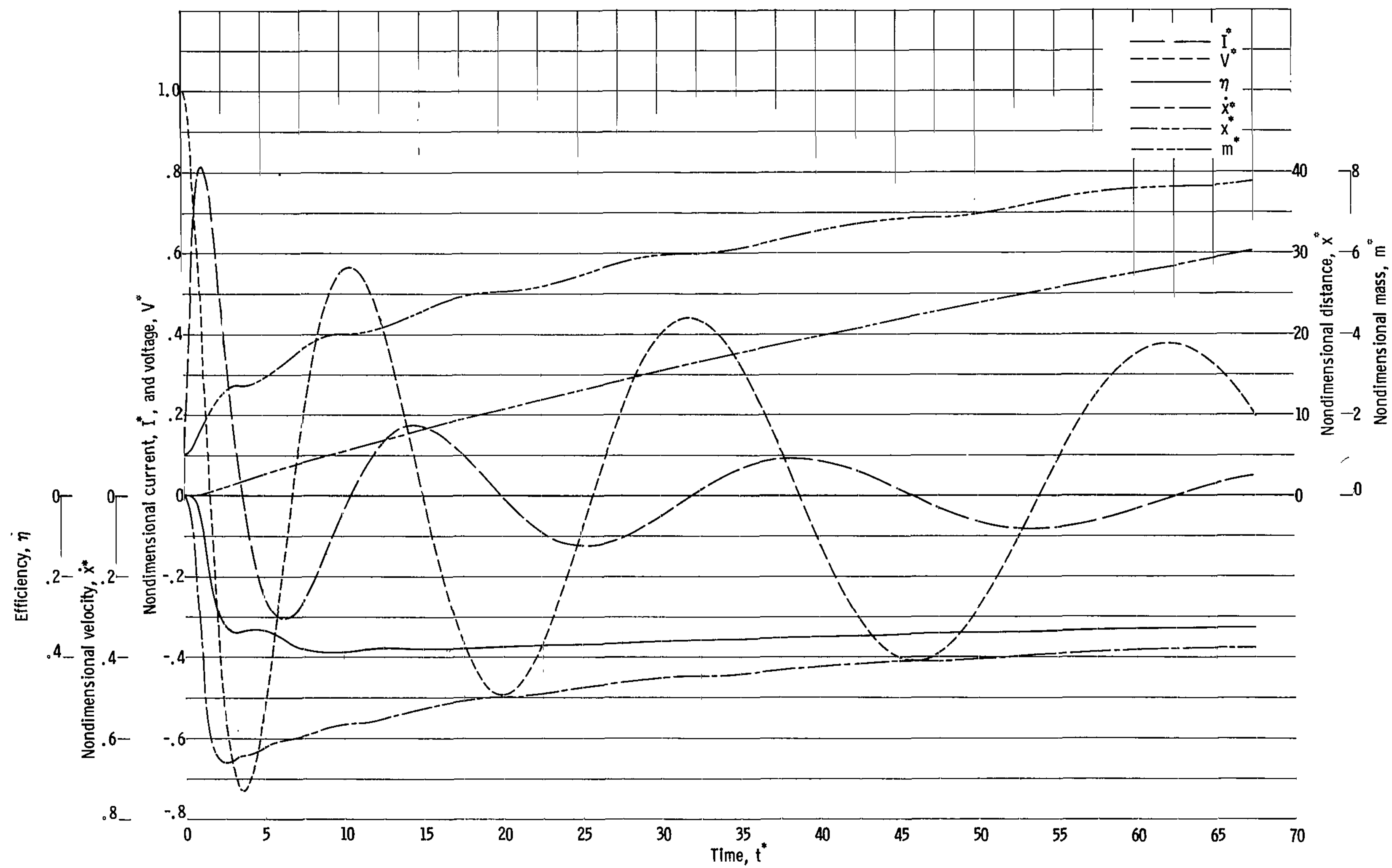
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(b-1) Nondimensional initial mass, 0.1.

(b) Circuit damping parameter, 0.0224, electromechanical interaction parameter, 1.667.

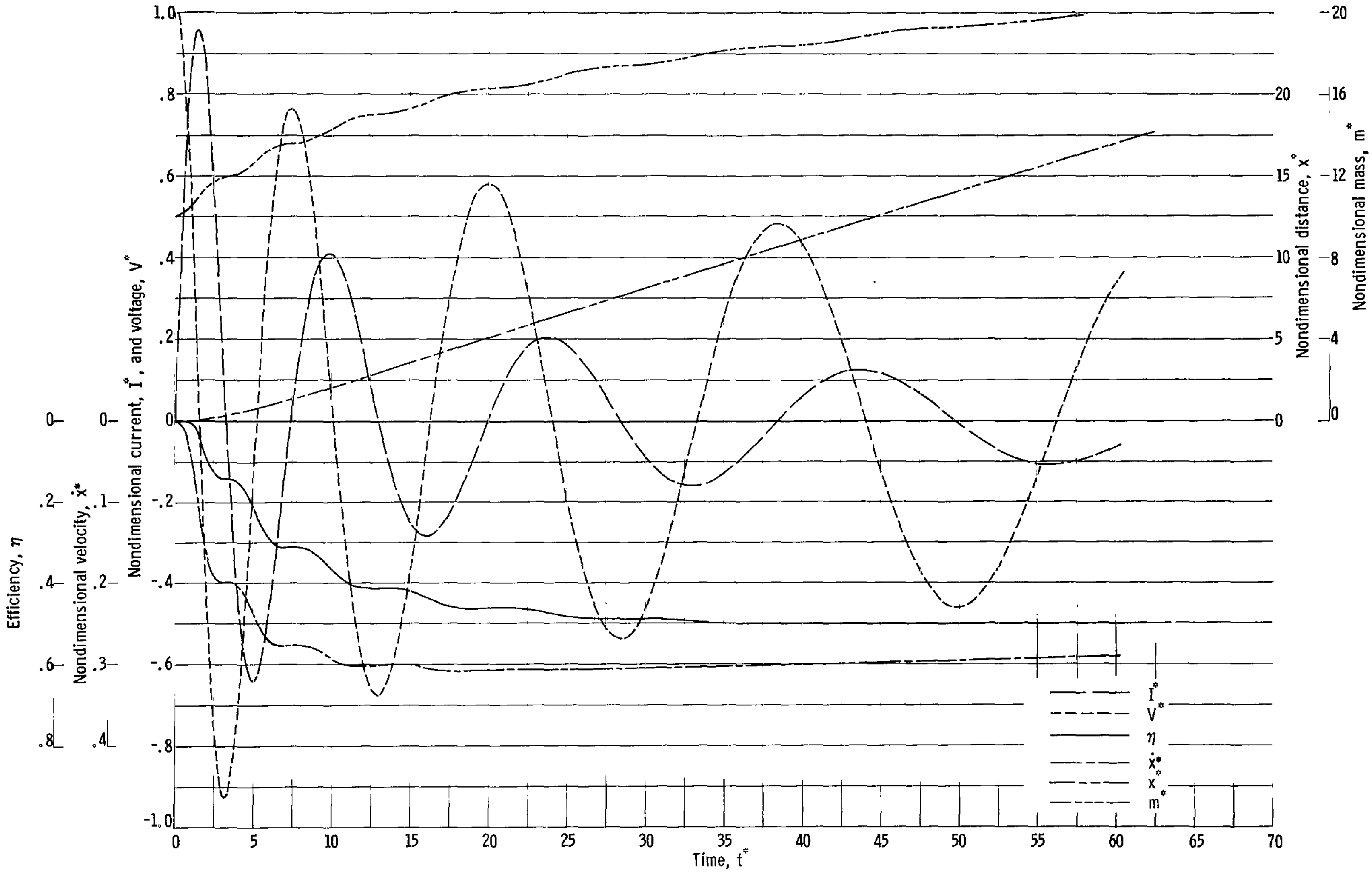
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(b-2) Nondimensional initial mass, 1.

(b) Continued. Circuit damping parameter 0.0224, electromechanical interaction parameter, 1.667.

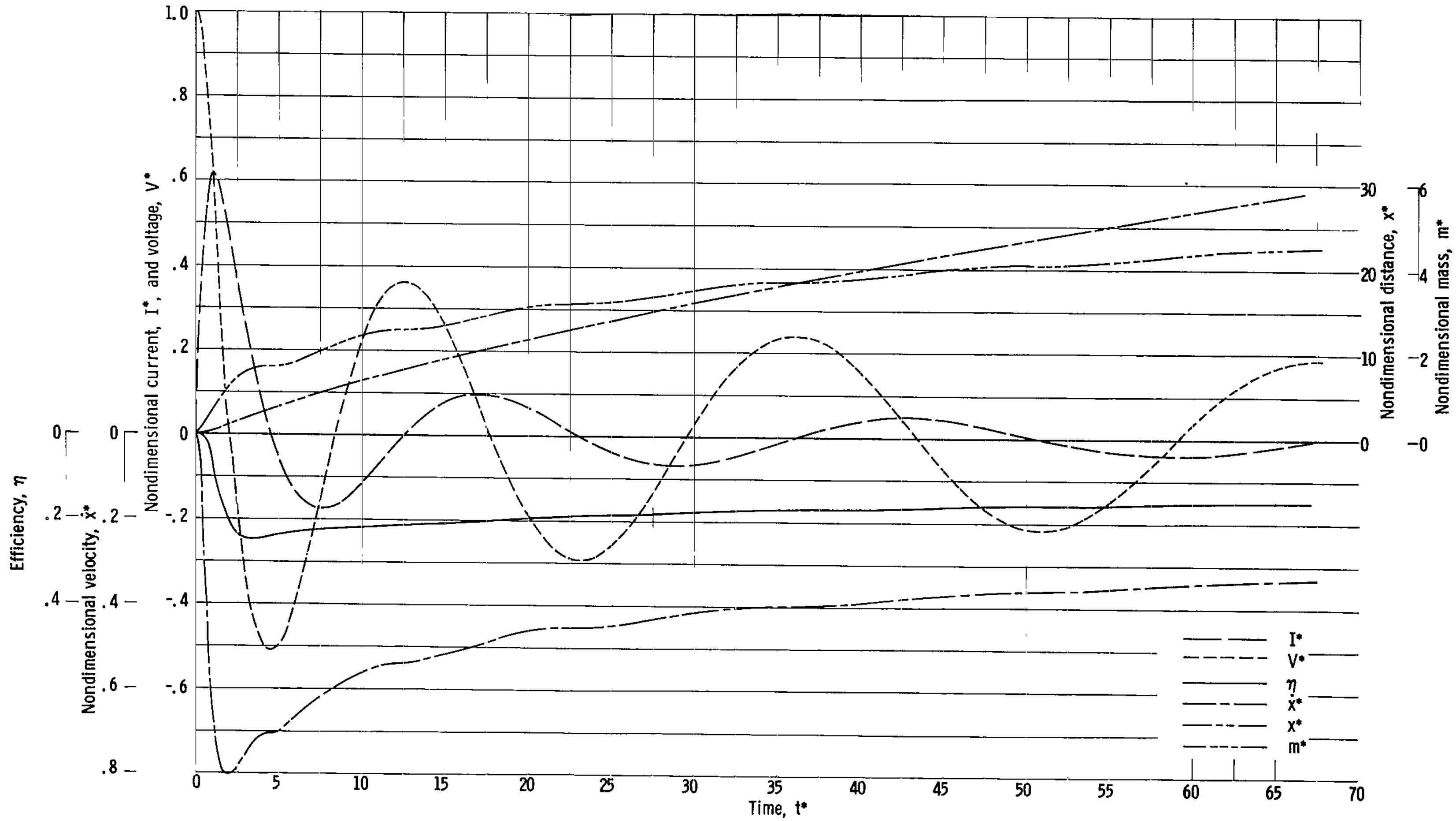
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(b-3) Nondimensional initial mass, 10.

(b) Concluded. Circuit damping parameter, 0.0224, electromechanical interaction parameter, 1.667.

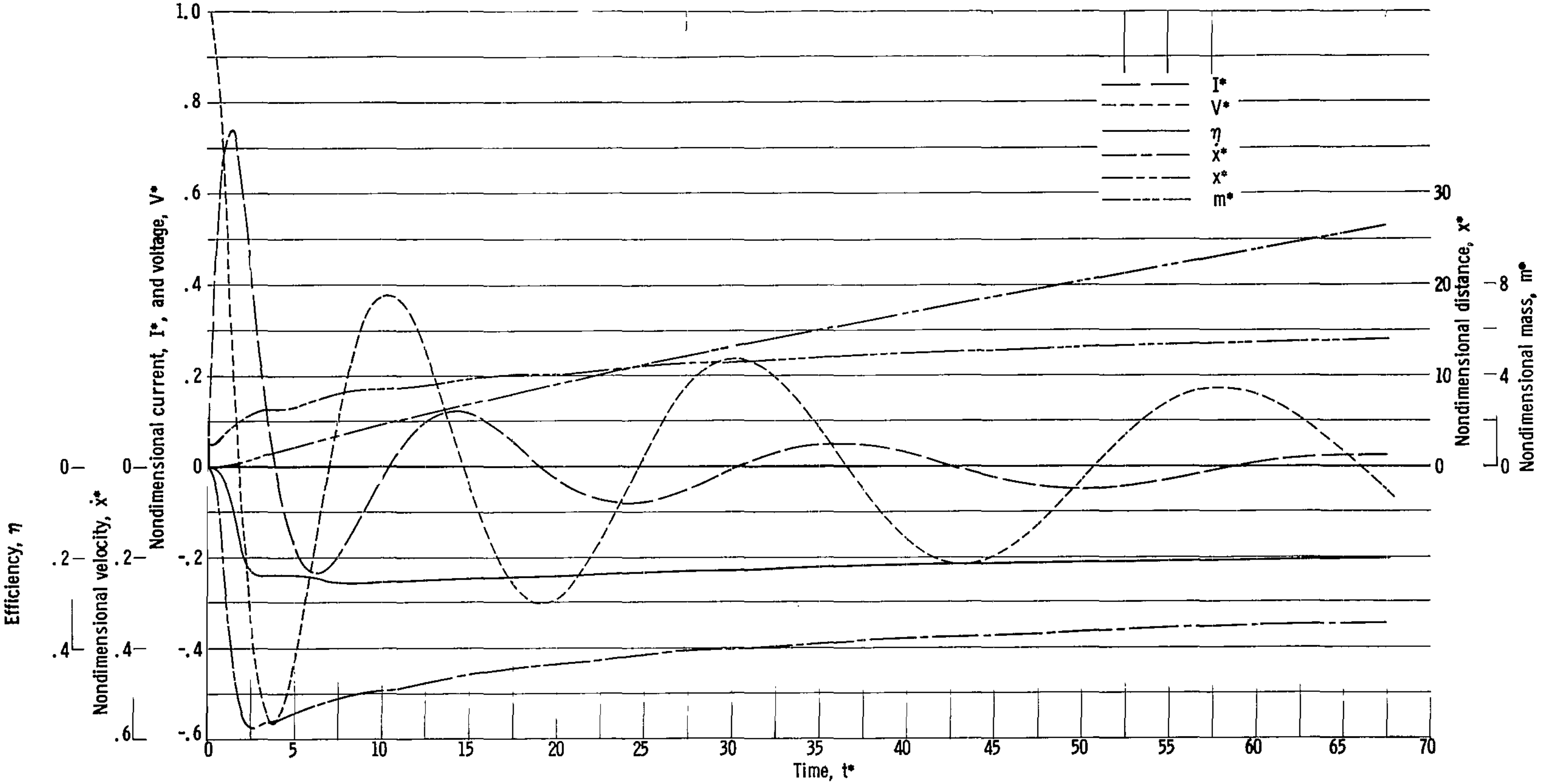
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(c-1) Nondimensional initial mass, 0.1.

(c) Circuit damping parameter, 0.2236; electromechanical interaction parameter, 1.667.

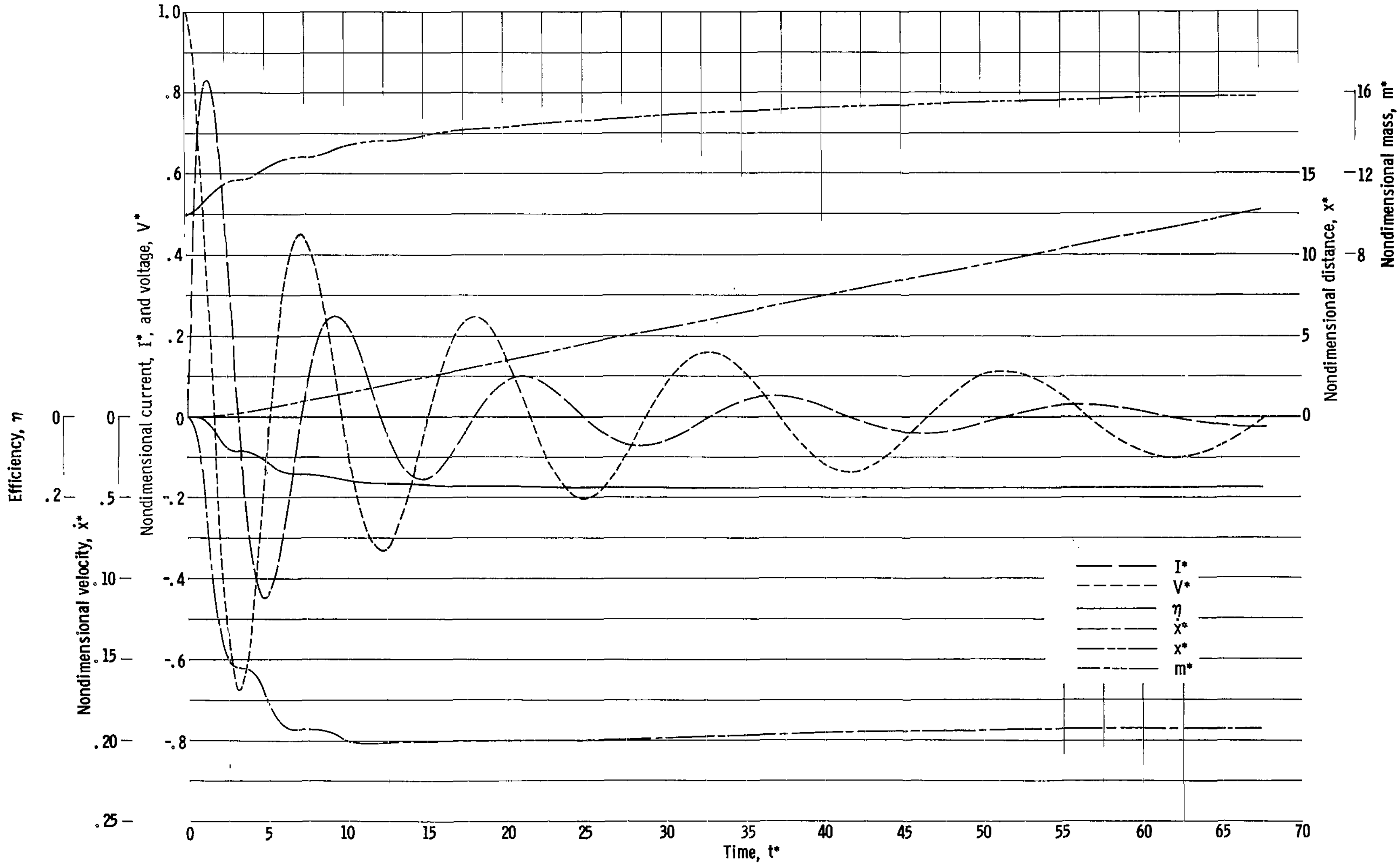
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(c-2) Nondimensional initial mass, 1.

(c) Continued. Circuit damping parameter, 0.2236; electromechanical interaction parameter, 1.667.

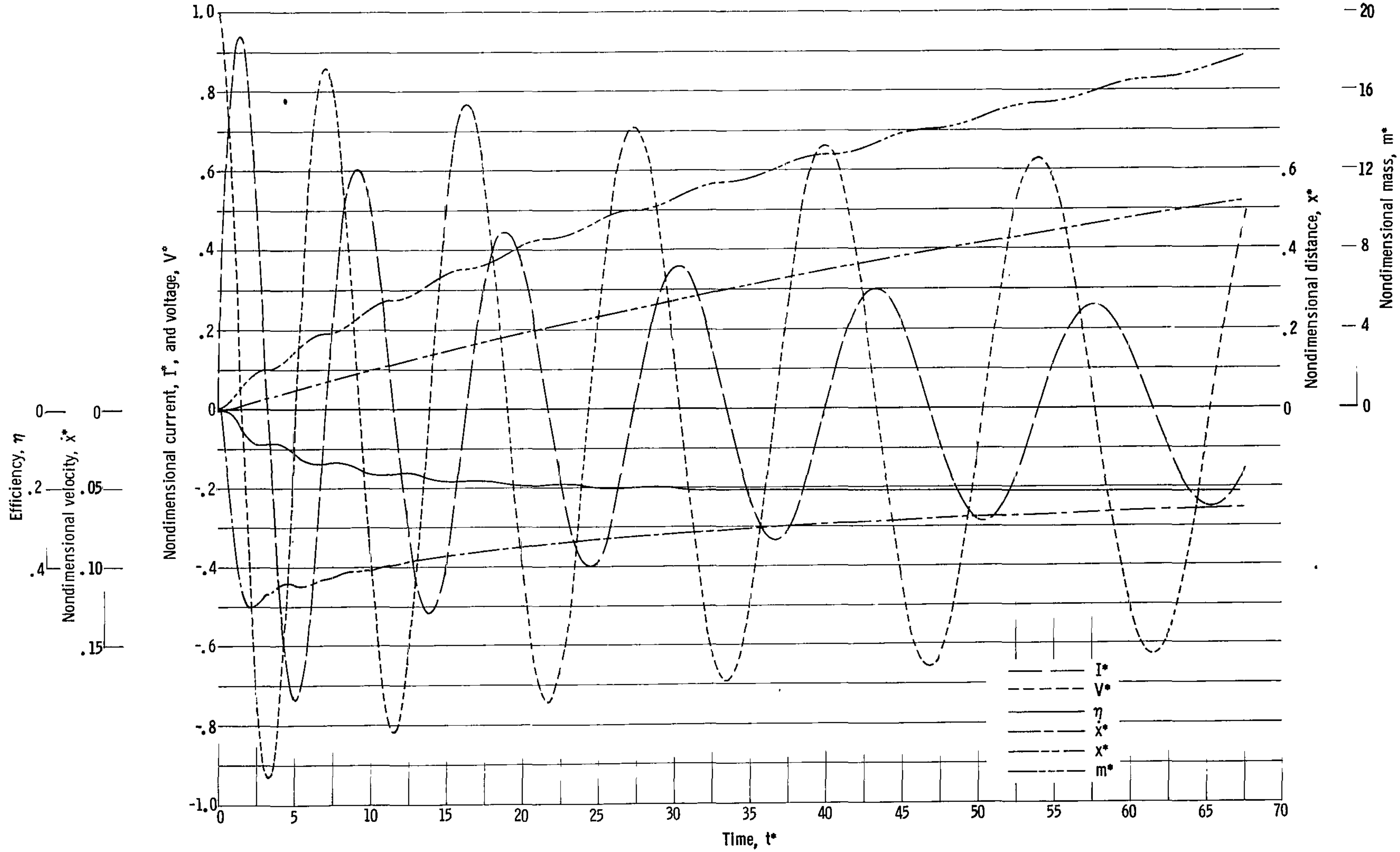
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(c-3) Nondimensional initial mass, 10.

(c) Concluded. Circuit damping parameter, 0.2236; electromechanical interaction parameter, 1.667.

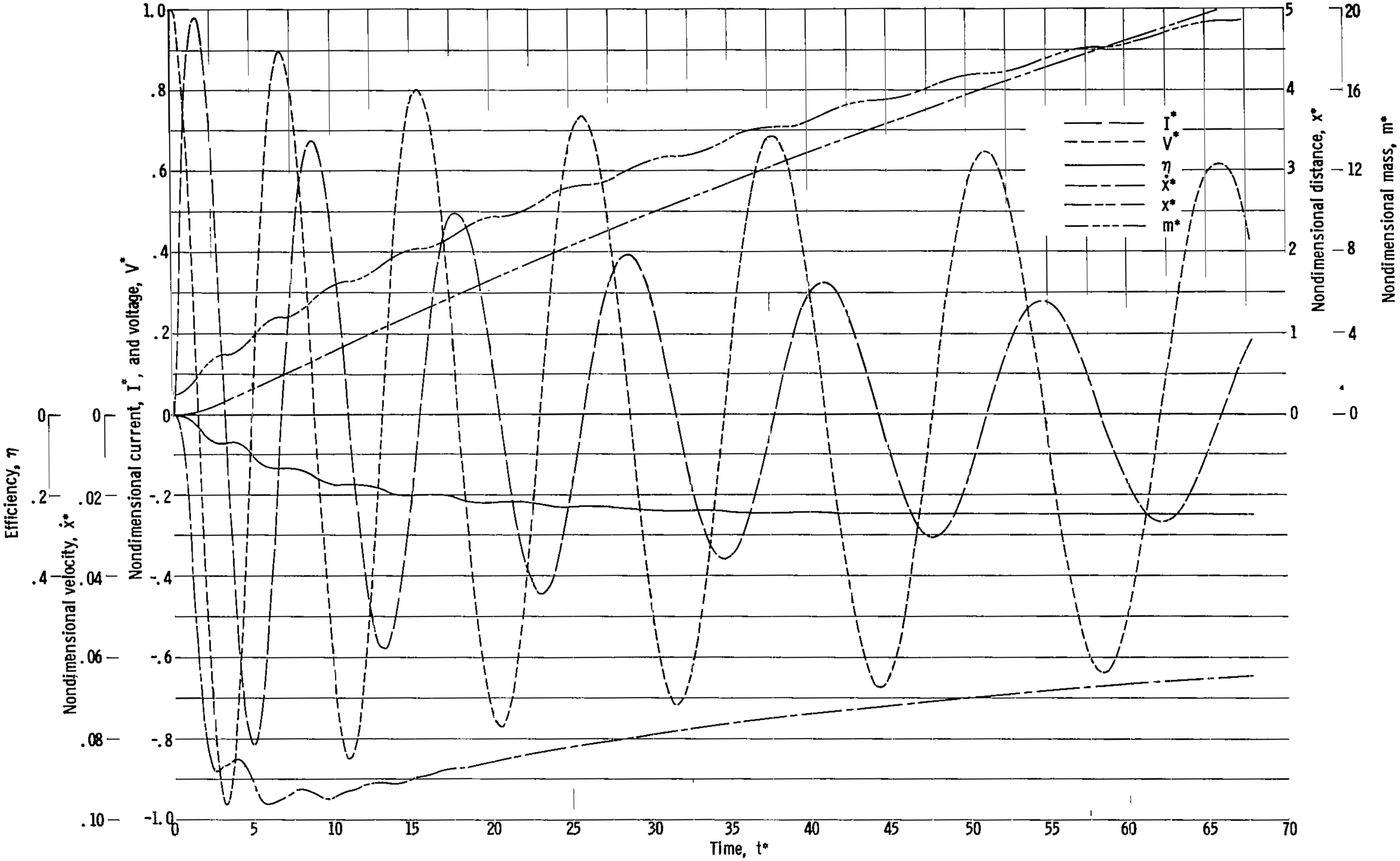
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(d-1) Nondimensional initial mass, 0.1.

(d) Circuit damping parameter, 0.0022; electromechanical interaction parameter, 0.1667.

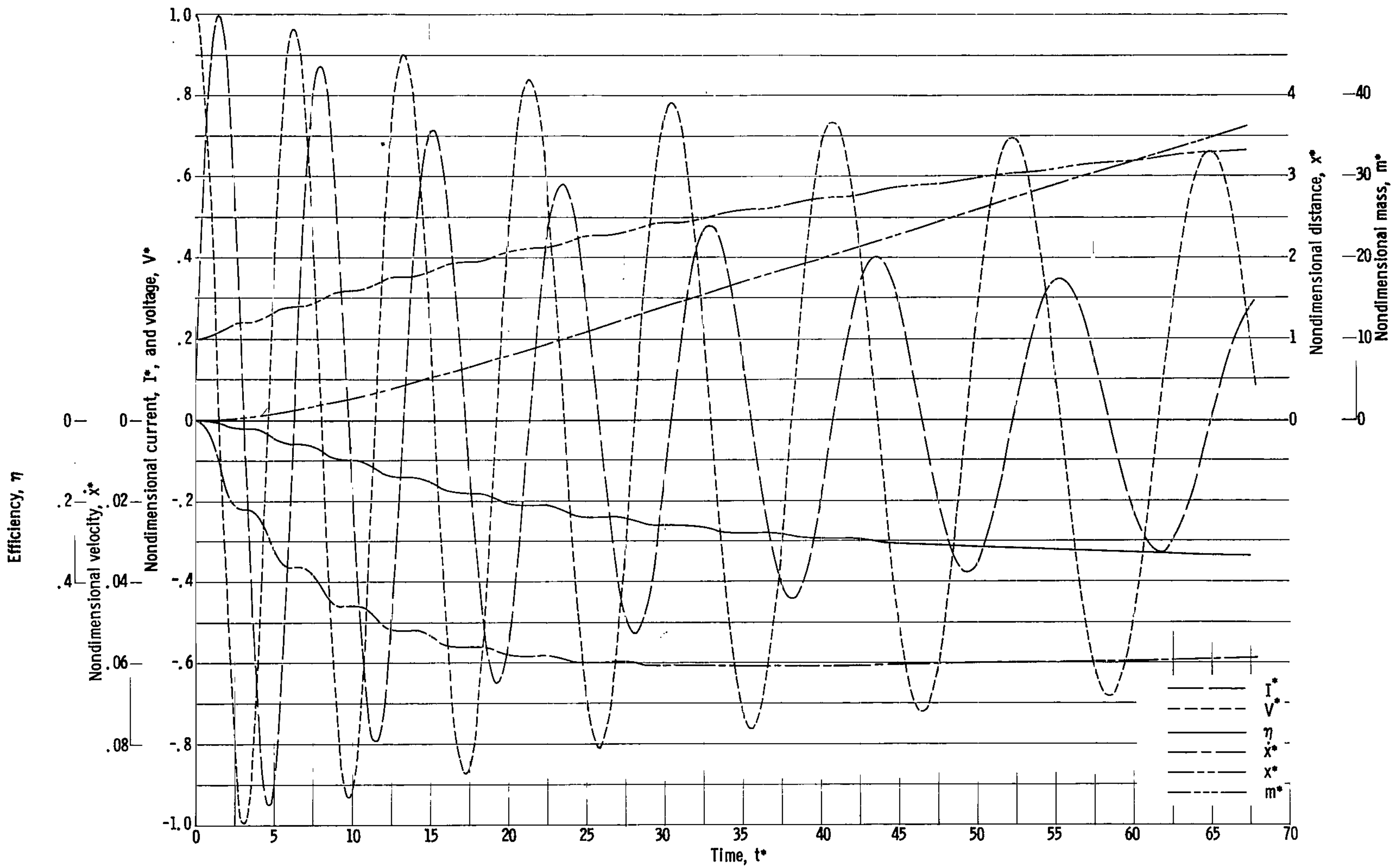
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(d-2) Nondimensional initial mass, 1.

(d) Continued. Circuit damping parameter, 0.0022; electromechanical interaction parameter, 0.1667.

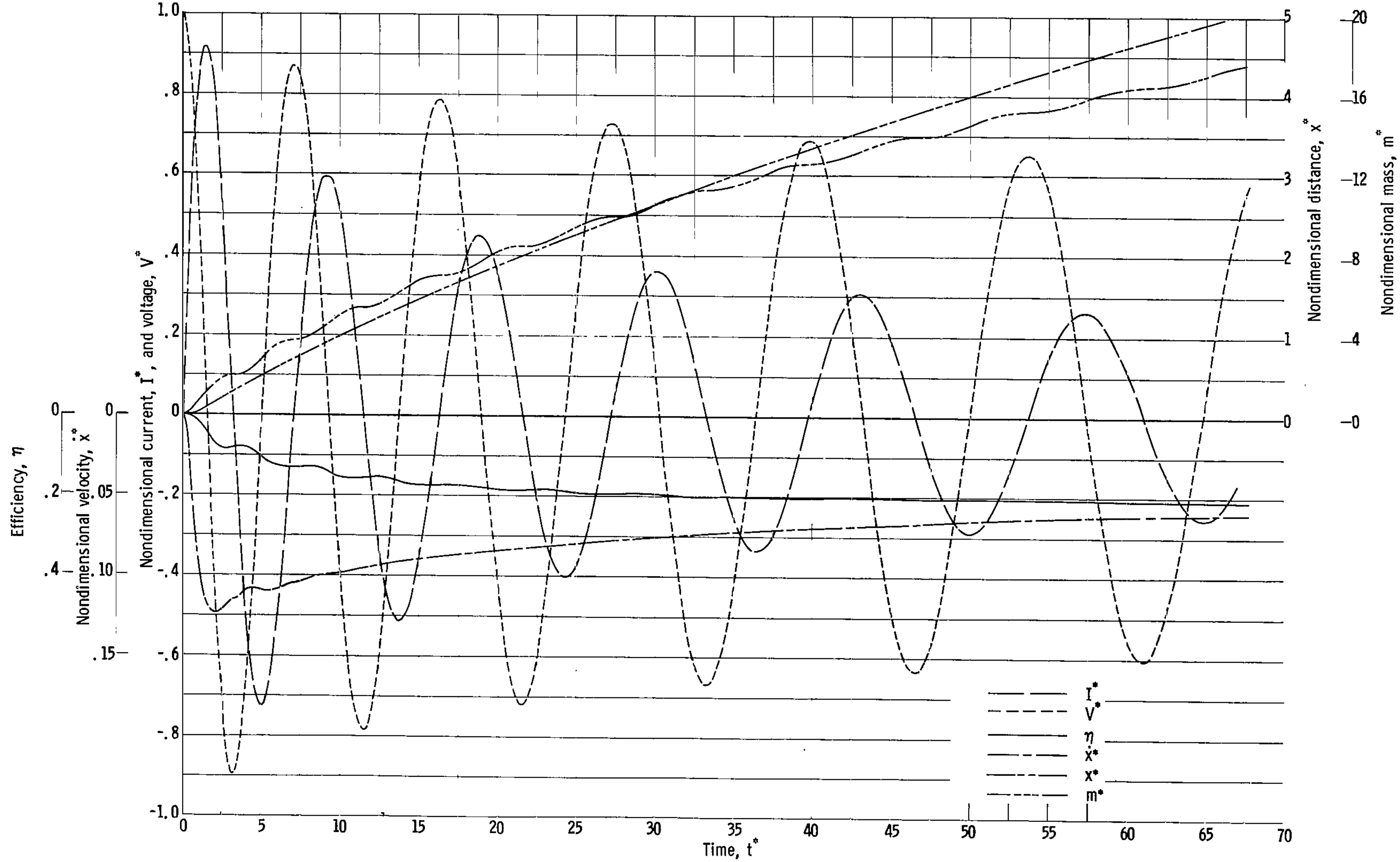
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(d-3) Nondimensional initial mass, 10.

(d) Concluded. Circuit damping parameter, 0.0022; electromechanical interaction parameter, 0.1667.

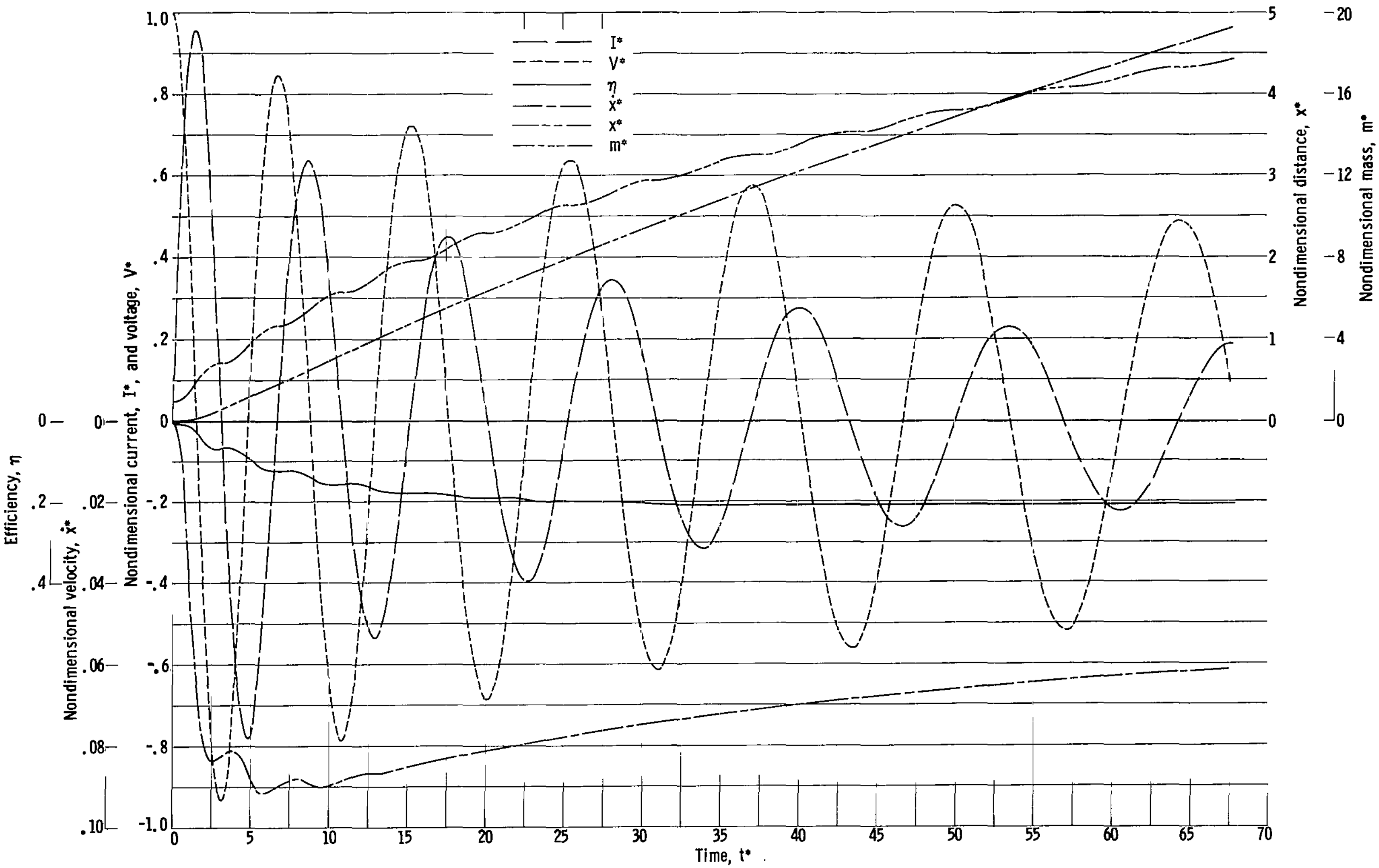
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(e-1) Nondimensional initial mass, 0.1.

(e) Circuit damping parameter, 0.0224; electromechanical interaction parameter, 0.1667.

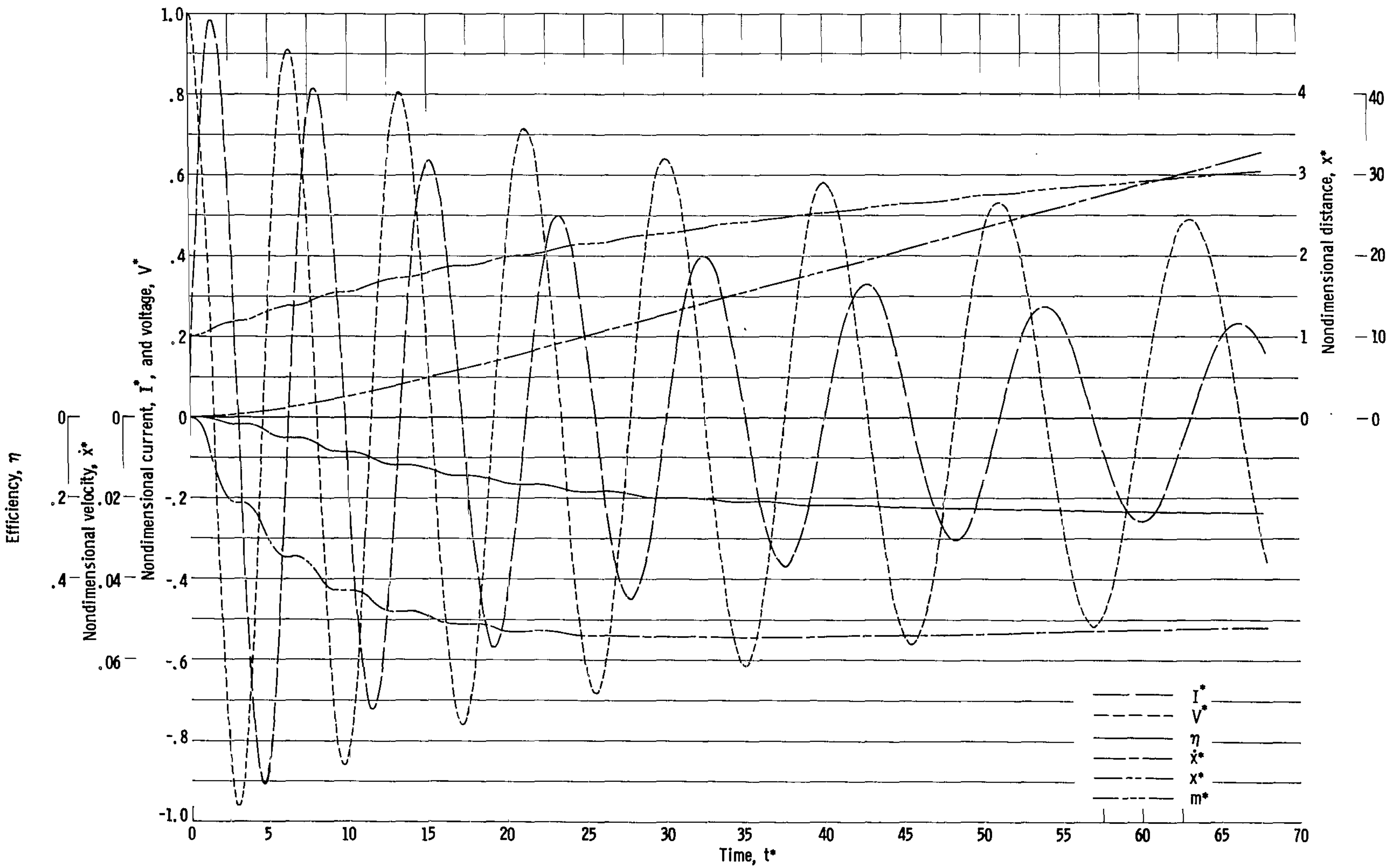
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(e-2) Nondimensional initial mass, 1.

(e) Continued. Circuit damping parameter, 0.0224; electromechanical interaction parameter, 0.1667.

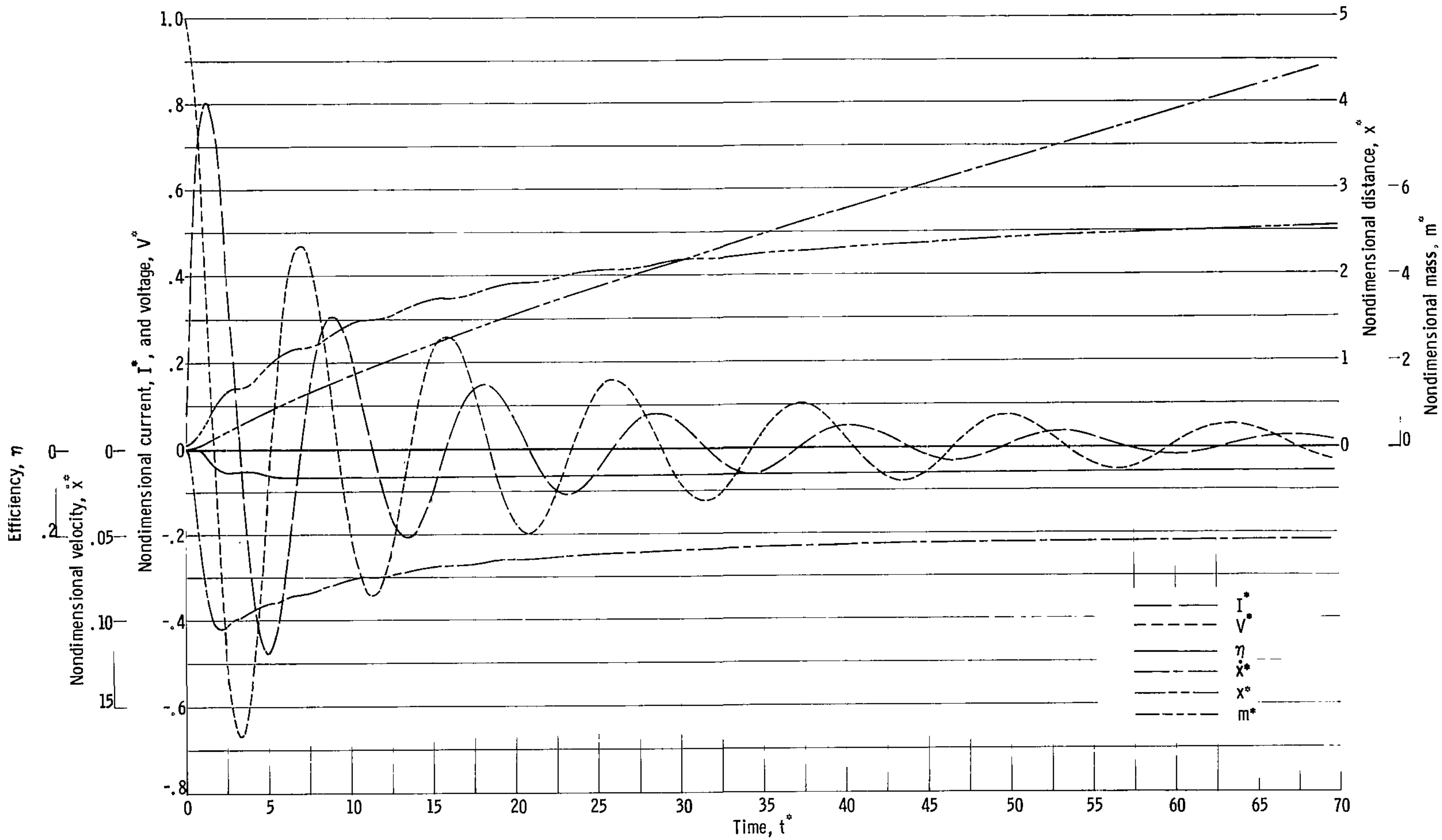
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(e-3) Nondimensional initial mass, 10.

(e) Concluded. Circuit damping parameter, 0.0224; electromechanical interaction parameter, 0.1667.

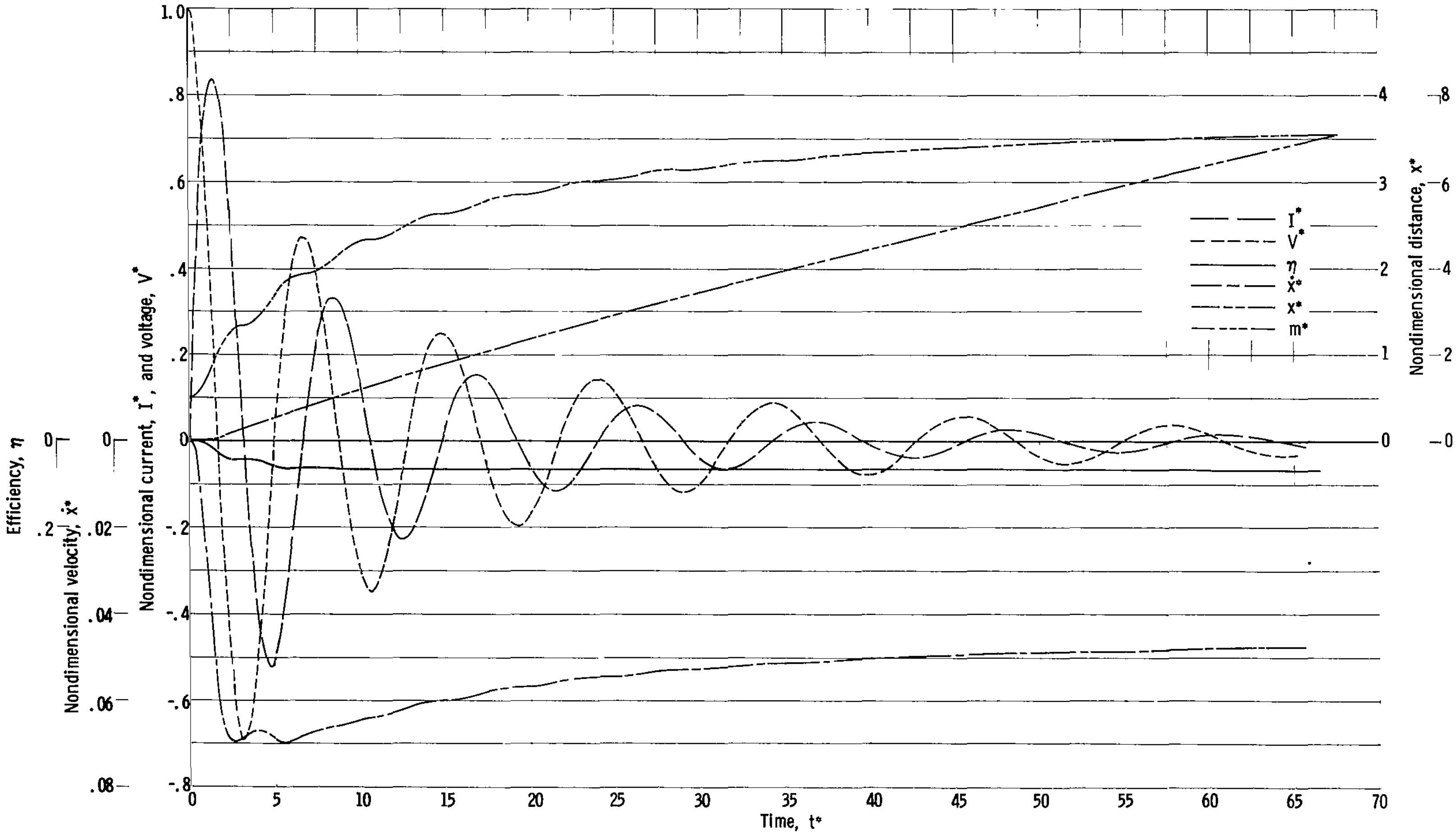
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(f-1) Nondimensional initial mass, 0.1.

(f) Circuit damping parameter, 0.2236; electromechanical interaction parameter, 0.1667.

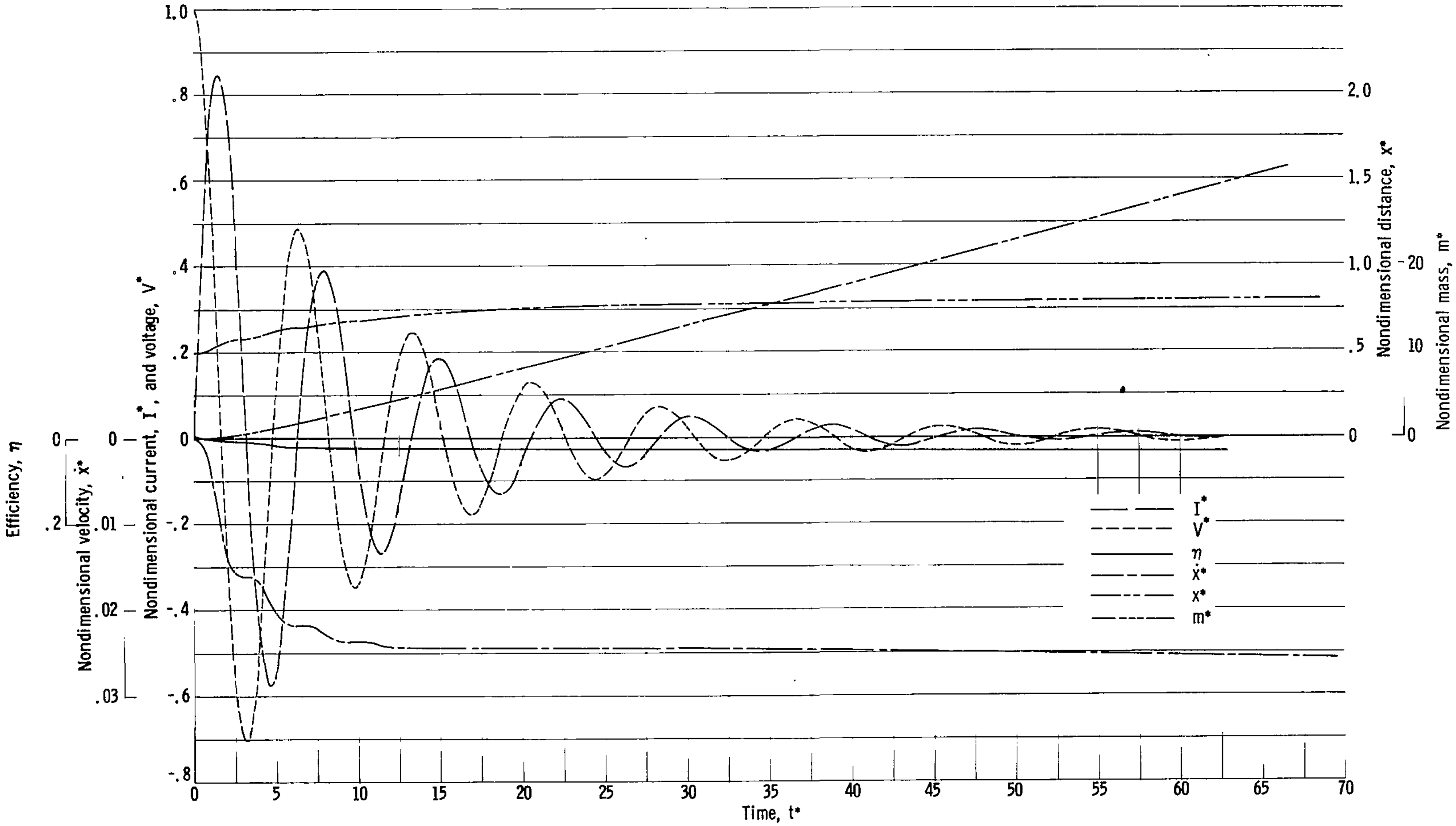
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(f-2) Nondimensional initial mass, 1.

(f) Continued. Circuit damping parameter, 0.2236; electromechanical interaction parameter, 0.1667.

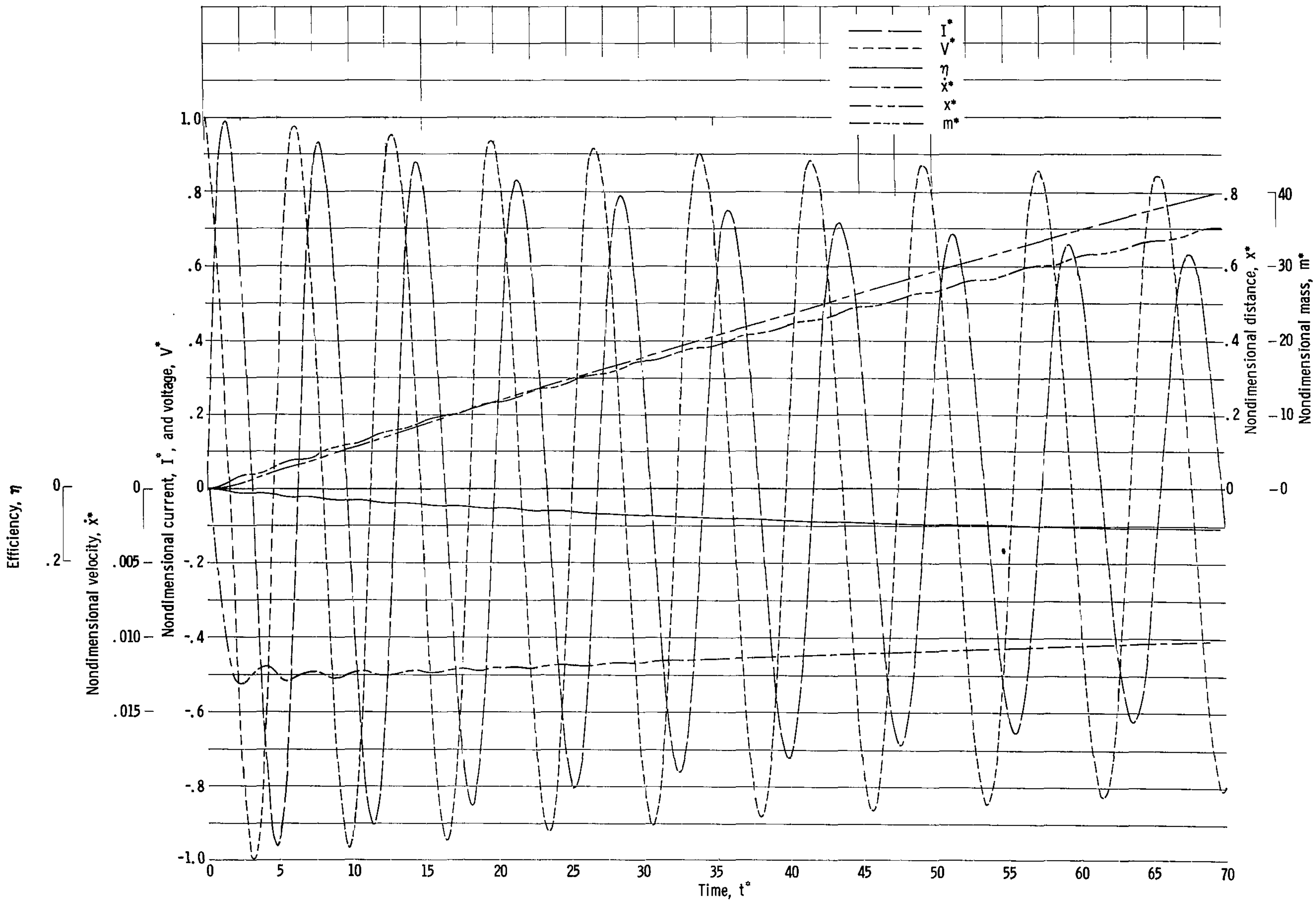
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(f-3) Nondimensional initial mass, 10.

(f) Concluded. Circuit damping parameter, 0.2236; electromechanical interaction parameter, 0.1667.

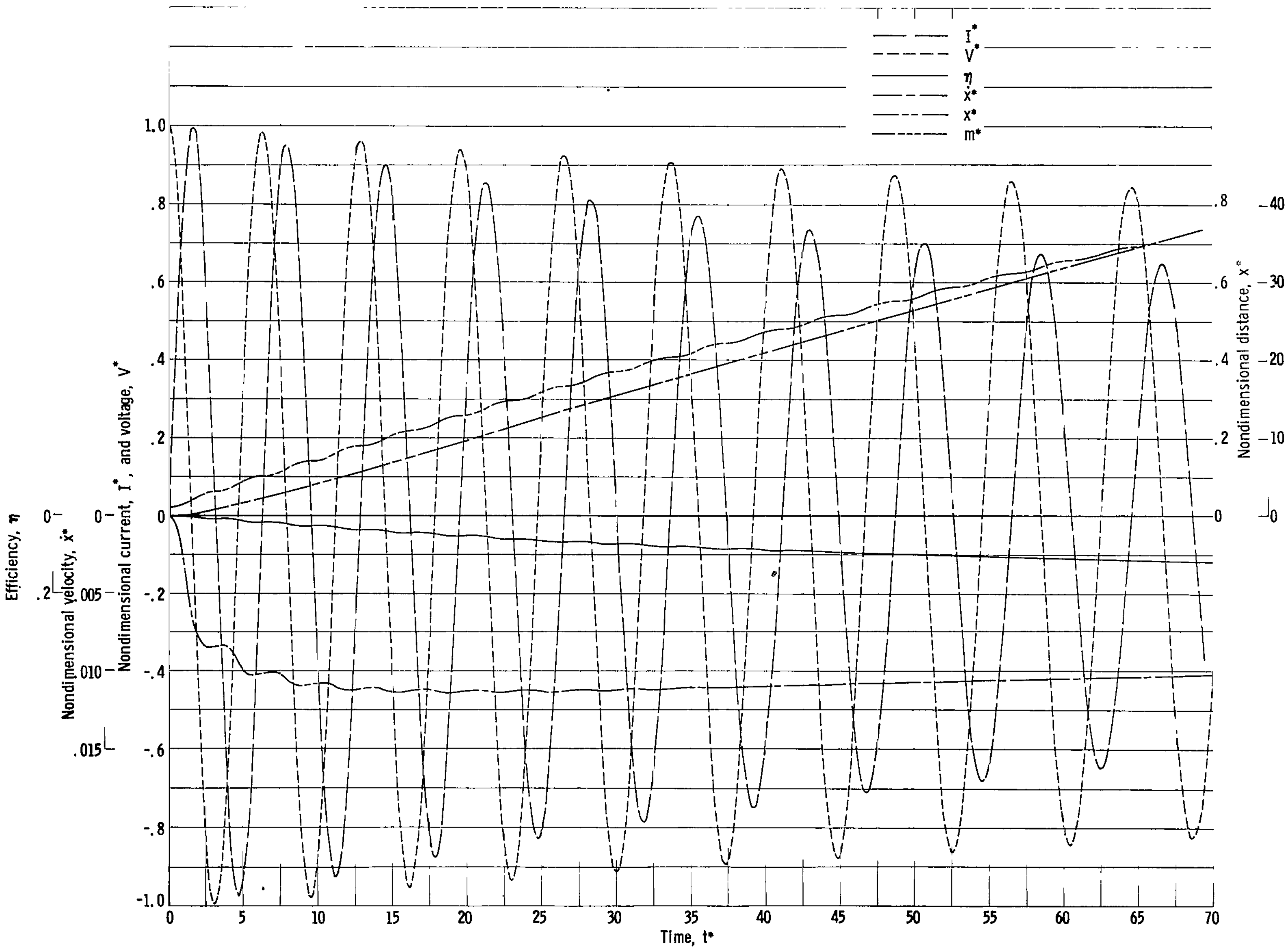
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(g-1) Nondimensional initial mass, 0.1.

(g) Circuit damping parameter, 0.0022; electromechanical interaction parameter, 0.0167.

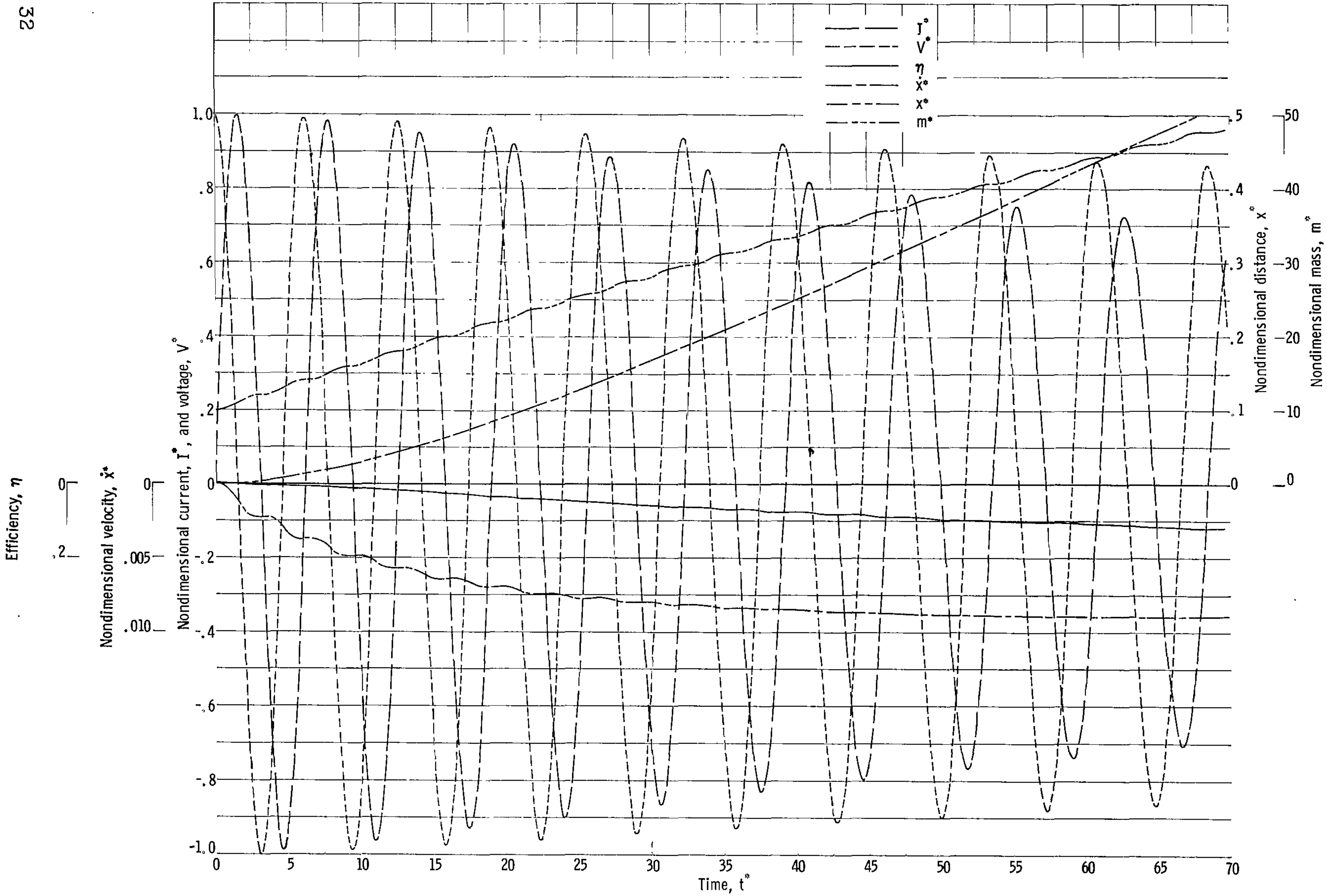
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(g-2) Nondimensional initial mass, 1.

(g) Continued. Circuit damping parameter, 0.0022; electromechanical interaction parameter, 0.0167.

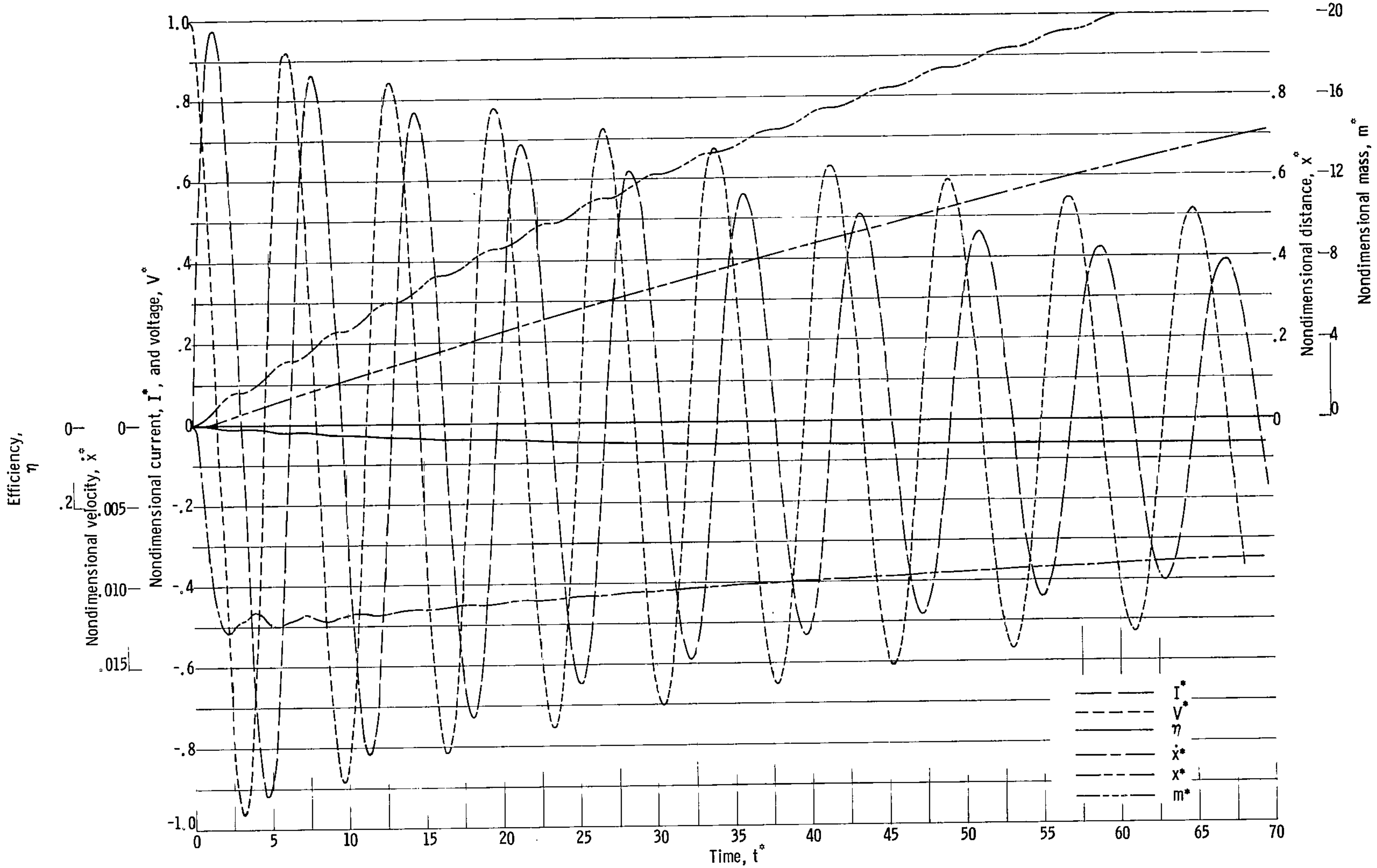
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(g-3) Nondimensional initial mass, 10.

(g) Concluded. Circuit damping parameter, 0.0022; electromechanical interaction parameter, 0.0167.

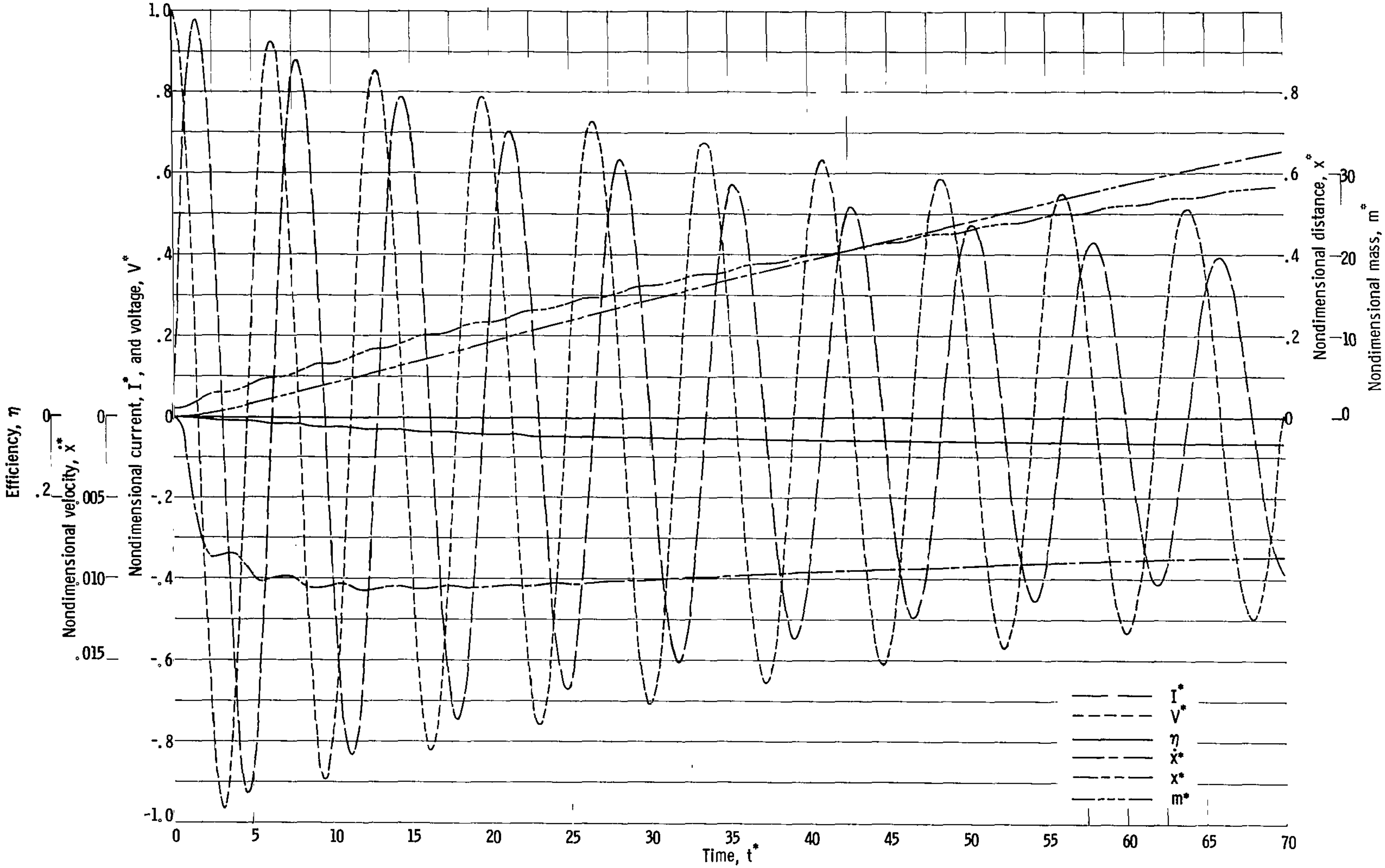
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(h-1) Nondimensional initial mass, 0.1.

(h) Circuit damping parameter, 0.0224; electromechanical interaction parameter, 0.0167.

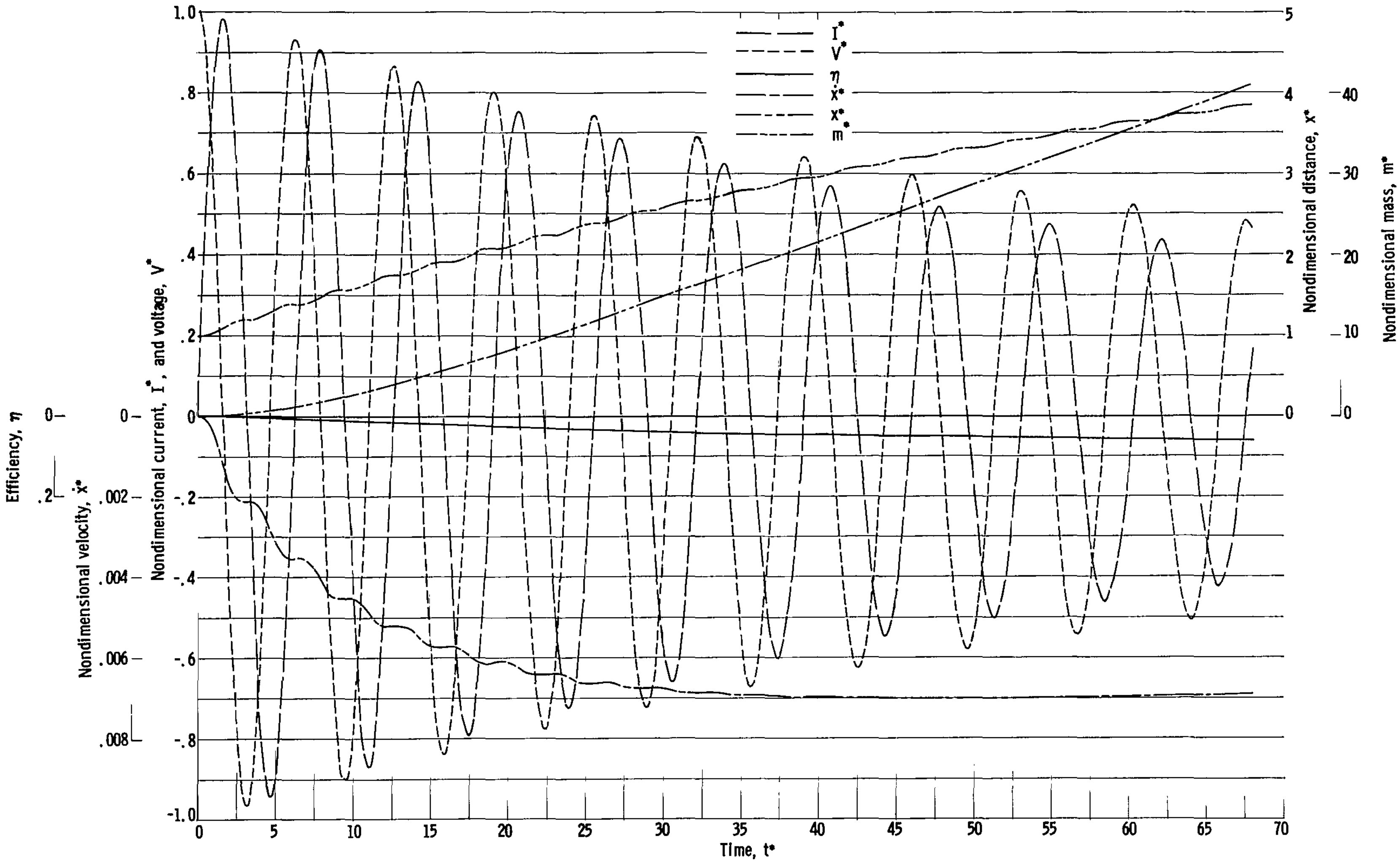
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(h-2) Nondimensional initial mass, 1.

(h) Continued. Circuit damping parameter, 0.0224; electromechanical interaction parameter, 0.0167.

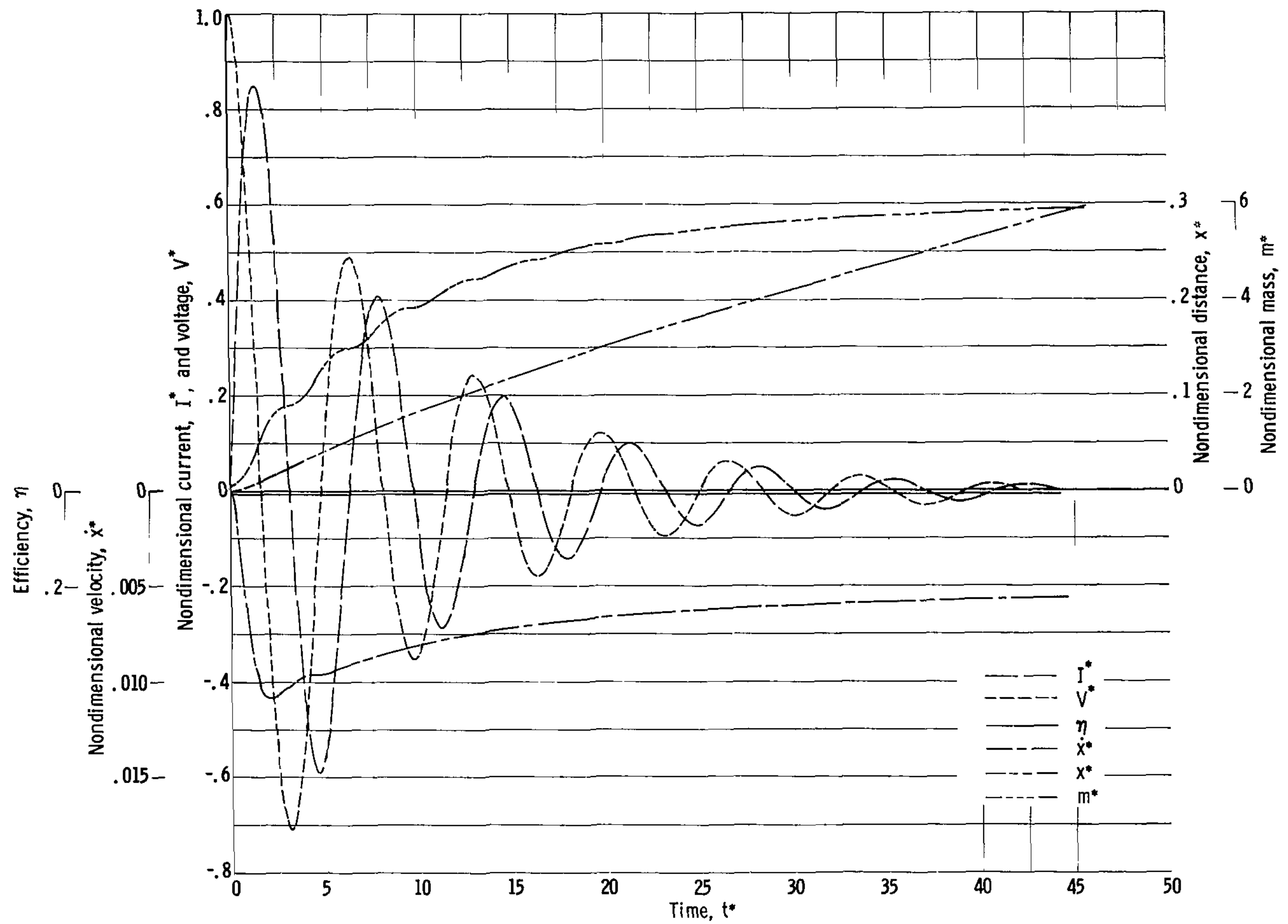
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(h-3) Nondimensional initial mass, 10.

(h) Concluded. Circuit damping parameter, 0.0224; electromechanical interaction parameter, 0.0167.

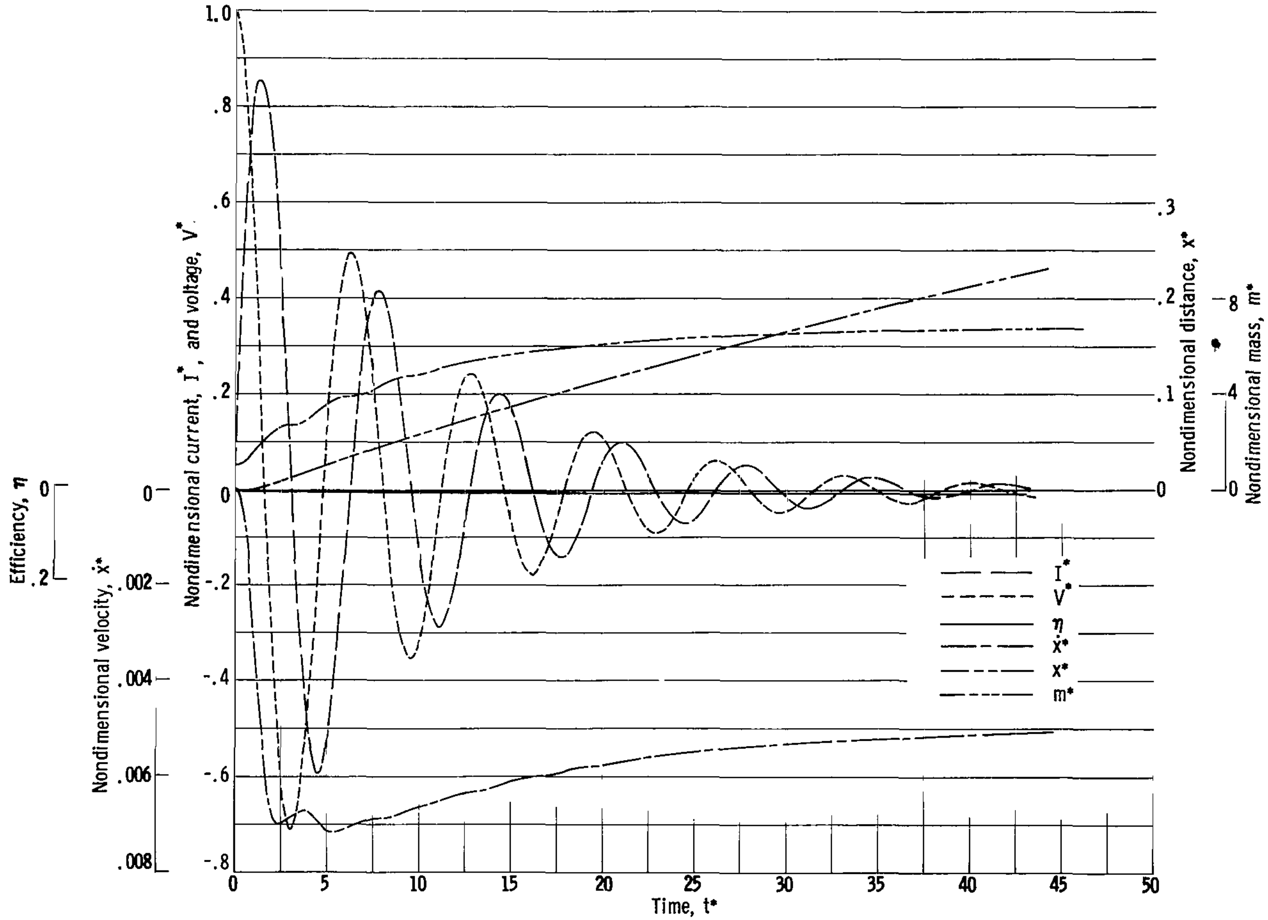
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(i-1) Nondimensional initial mass, 0.1.

(i) Circuit damping parameter, 0.2236; electromechanical interaction parameter, 0.0167.

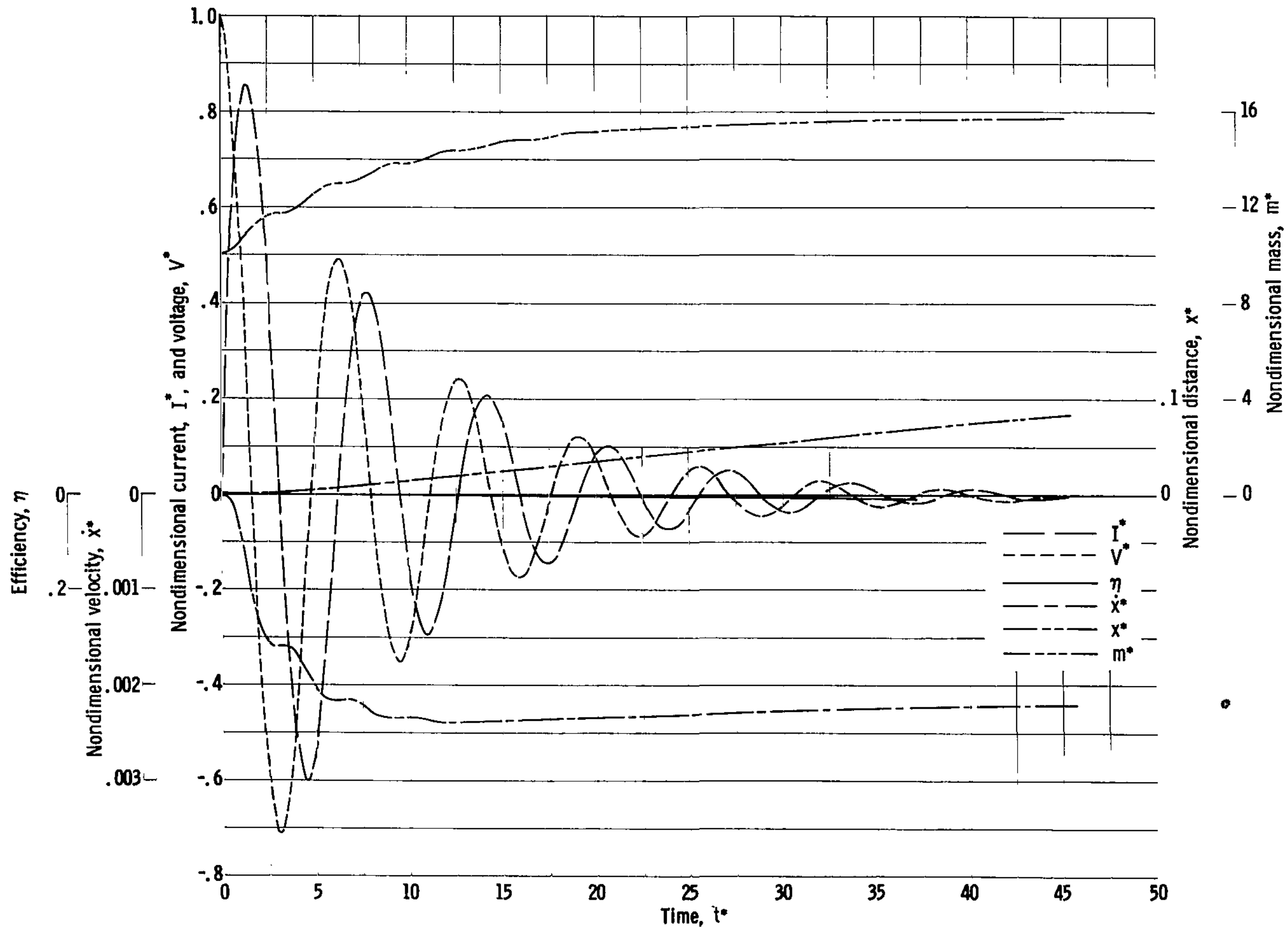
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(i-2) Nondimensional initial mass, 1.

(i) Continued. Circuit damping parameter, 0.2236; electromechanical interaction parameter, 0.0167.

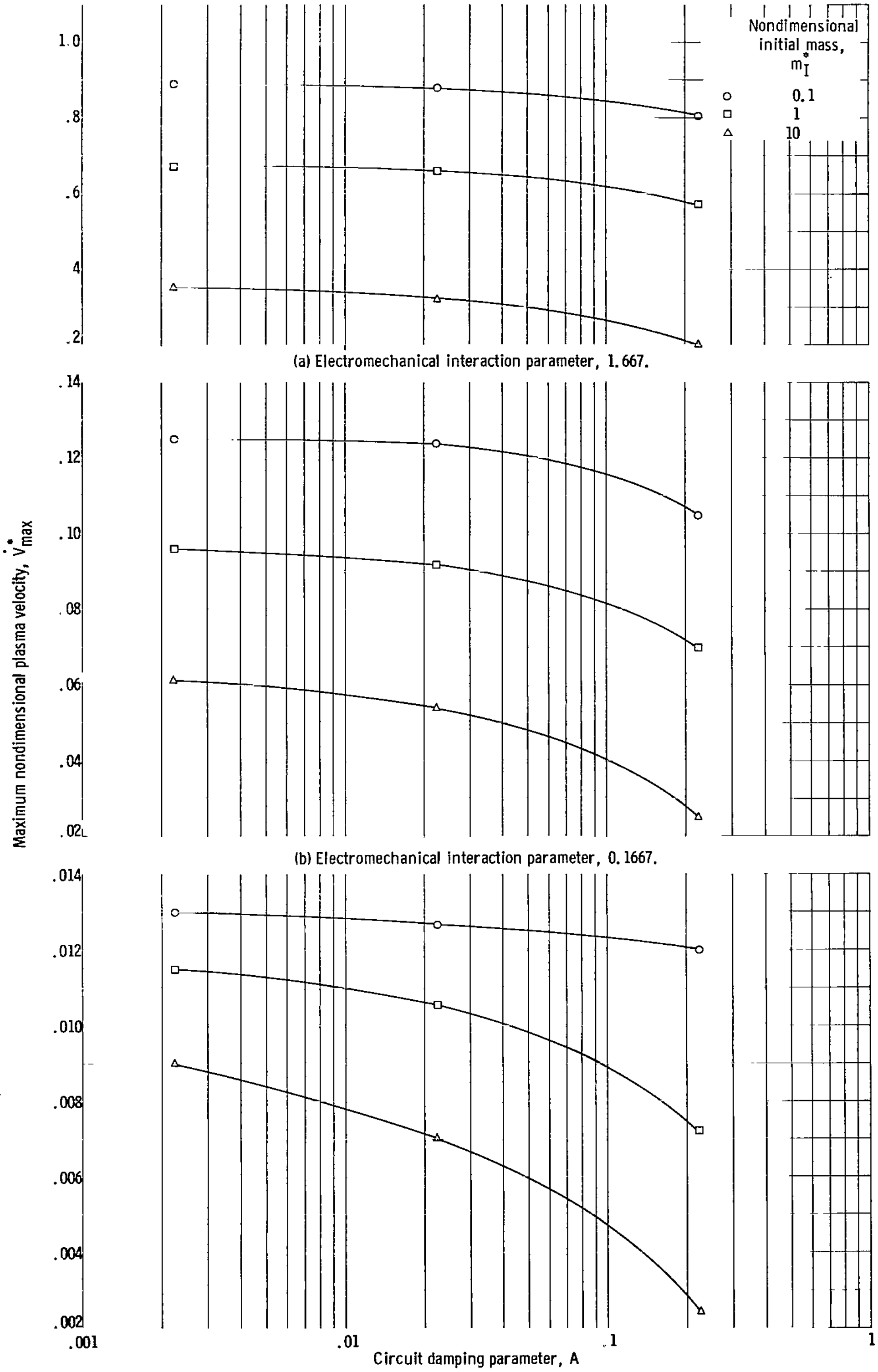
Figure 3. - Continued. Analog solutions of plasma accelerator equations.



(i-3) Nondimensional initial mass, 10.

(i) Concluded. Circuit damping parameter, 0.2236; electromechanical interaction parameter, 0.0167.

Figure 3. - Concluded. Analog solutions of plasma accelerator equations.



(c) Electromechanical interaction parameter, 0.0167.

Figure 4. - Effect of circuit parameters on plasma maximum velocity.

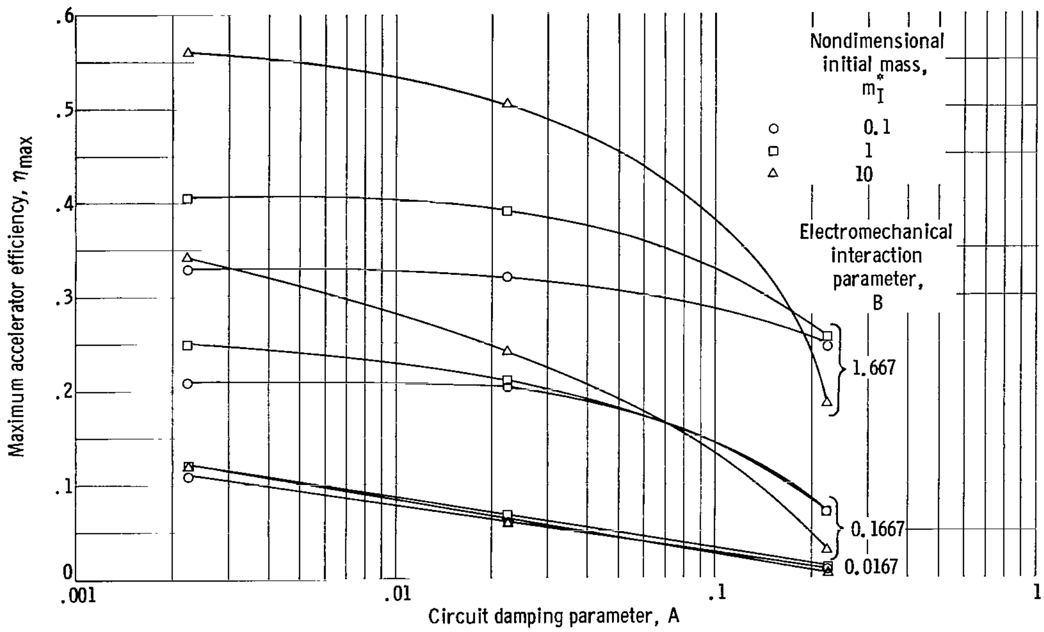


Figure 5. - Effect of circuit parameters on accelerator efficiency.

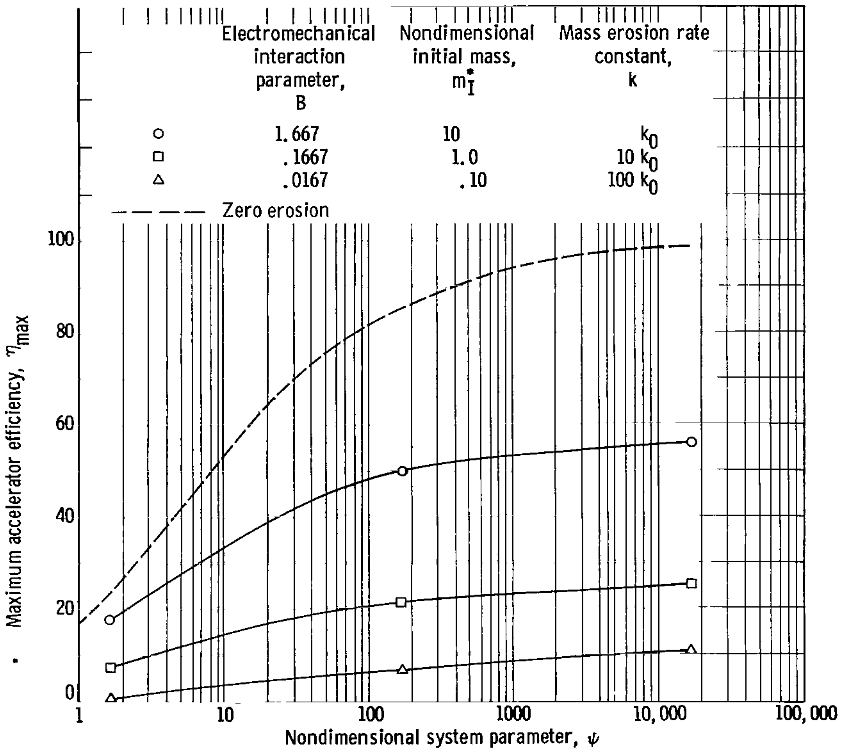


Figure 6. - Effect of mass erosion on maximum efficiency.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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